HUMID

Report on the cross-cutting methodology of the project

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Drought

Definition of drought

The definition of drought is as complex as the phenomenon itself. Many authors debated about the best possible definition to avoid confusion in the terms used by the community studying drought and associated processes. The primary confusion comes from the difference between drought and water scarcity. For many years, drought was a term used for the phenomenon causing lack of availability of water for human consumption, which is an intuitive use of the traditional term of drought. Palmer (1965) definition is one of this type: "drought is an interval of time, generally of the order of months or years in duration, during which the actual moisture supply at a given place rather consistently falls short of the climatically expected or climatically appropriate moisture supply". Such a definition is tuned for a particular aspect of drought which is agricultural drought.

The reviews and dedicated articles tackling this issue suggested the convenience of using drought for the natural phenomenon consisting in a deficiency of water availability in the natural system and water scarcity as the water deficiency related to the use of water by humans (Pereira et al., 2002).

An example of the first case is the one of Sheffield and Wood (2011), who defined drought as "a deficit of water relative to normal conditions", leaving to the reader the freedom to assign the definition to the component of the natural system of interest of the reader (meteorological, agricultural, hydrological...). An additional important aspect of drought is that its definition closely depends on its time span and location.

Short, mid a long-term climatic variability (AghaKouchak et al., 2015) are under the sequence of anomalies propagating from the climatic system (e.g. precipitation, evapotranspiration) to the land surface (soil moisture, of an agricultural or environmental scope; or runoff, of a hydrologic scope) (Mishra and Singh, 2000). Thus, depending on the specific variables and the field of interest, studies often refer to meteorological, agricultural/environmental, and hydrologic drought (Wilhite , 2005). The IPCC provides specific drought definitions for each of the types of drought within the natural system:

- Meteorological drought: corresponds to a period when precipitation is considerably lower than its average level extending over a large area and spanning an extensive period of time. However, rainfall has limitations as a measure of water availability in droughts since it takes no account of evapotranspiration anomalies. Effective rainfall is more accurate but requires evapotranspiration data. The indirect nature of evapotranspiration limits its data availability (Tate and Gustard, 2000).

- Soil moisture drought (also known as agricultural drought): is due to a deficit of water in the soil's unsaturated zone (mostly in the root zone), depending on the specific needs of vegetation or crop. Soil moisture deficits have important impacts on natural ecosystems and agriculture.

- Hydrological drought: occurs when streamflows and water levels in rivers, lakes, and groundwater are low. Groundwater drought and streamflow drought are sometimes defined separately as below-normal groundwater levels and below-normal river discharge (Van Loon, 2015).

Any of these types of drought aims to define its intensity, duration and spatial extent to fully portray the characteristics of the drought (Tate and Gustard, 2000). Meteorological and agricultural ground-based observations (Palmer, 1965, Gallagher et al., 1976) have been the traditional data source to analyze droughts (Hayes et al., 1999; Santos et al., 2010; Aghakouchak et al., 2014; Sheffield et al., 2012). However, beyond this traditional approach, the analysis of drought faces important challenges regarding the availability and suitability of specific data such as soil moisture or evapotranspiration (AghaKouchak and Nakhjiri , 2012) required to understand the complex interactions under the evolution of drought.

Nowadays it is common to distinguish drought as a natural phenomenon and water scarcity as a human-caused processes of overexploitation of water resources when demand for water is higher than water availability (Tallaksen & Van Lanen, 2004, Van Loon and Van Lanen, 2013). With the increasing number of studies approaching the evaluation of drought and its implications from multiple perspectives it became clear that this separation is convenient. Governmental organizations also adopted this distinction and provide a similar definition of water scarcity. For instance, the EU (2007) defined water scarcity as a situation where water resources become unable to satisfy long-term average requirements. It refers to long-term water imbalances, where demand exceeds the sustainable exploitation of water resources. Operational definitions of drought tend to incorporate the term water scarcity, due to their focus on the impacts of the water deficit to the socioeconomic system.

Drought is not a sequence but a complex phenomenon of interactions

Drought is a difficult phenomenon of complex interactions between atmospheric and continental surface processes (Van Loon, 2015) beyond the lack of rainfall caused by blocking high-pressure systems. Many atmospheric processes that are behind the development of drought as a result of climatic variability such as large-scale atmospheric or ocean patterns do not only affect rainfall anomalies. The impact of temperature, radiation and wind anomalies causing drought has been traditionally neglected in Europe due to the majority of drought studies coming from countries of wet temperate or cold climate areas. Areas of Mediterranean climate such as the Iberian Peninsula where periods of high energy input are common show meteorological anomalies of very responsive nature. Thus, the mechanism of drought onset in our geography corresponds better to those identified in other areas of high radiation, wind and evapotranspiration such as the Great Plains of North America (Otkin et al., 2013) than to the classifications of drought proposed from northern Europe (Van Loon et al., 2015, Table 2). Few studies have devoted attention to processes of drought generation rooting from variables beyond precipitation and temperature in Europe, with most of the works focused on temperature driven phenomena such as as heat waves seen as consequence of drought (Fischer et al., 2007; Seneviratne et al., 2013) more than as a imbalance in the land-surface system connected to the other hazards (Teuling et al., 2018; Miralles et al, 2019) similar to the approach followed in the United States before (Otkin et al., 2013). In the Iberian Peninsula and other southern climates of the continent, there is a need of studies with this integrative perspective and there are recent works on this direction: about flash droughts and its factors (Noguera et al., 2021) or on the interaction and propagation of anomalies between several relevant variables for drought (Gaona et al., 2021).

There are other aspects of droughts in semi-arid climates such as the Mediterranean that require specific attention due to the differences of their mechanisms in this region compared to other temperate and boreal regions of the world. The combined action of the atmospheric anomalies and associated consequences are generally considered to concentrate in summer (Sutanto et al., 2020), which is untrue in Mediterranean latitudes where anomalies causing impacts tend to occur in the rest of the seasons. Propagation of drought is also not following the general propagation scheme assumed by most of the drought community, such as the precedence of runoff drought to soil moisture drought proposed by Van Loon (2015). This traditional hydrologic perspective is valid for mountainous regions but not for the semi-arid inlands of the Mediterranean basin and Eurasia, where precipitation barely saturates the soil and consequently the runoff mechanism rarely dominates the system. Additionally, the runoff dominant perspective can be suitable for hydrologic management but not for drought implications to the environmental and agricultural worlds which strongly depend on soil moisture drought (Berg & Sheffield, 2018). Thus, we point out the need to develop specific analysis of drought mechanisms for the semi-arid regions, which comprise most of the area in the Ebro basin.

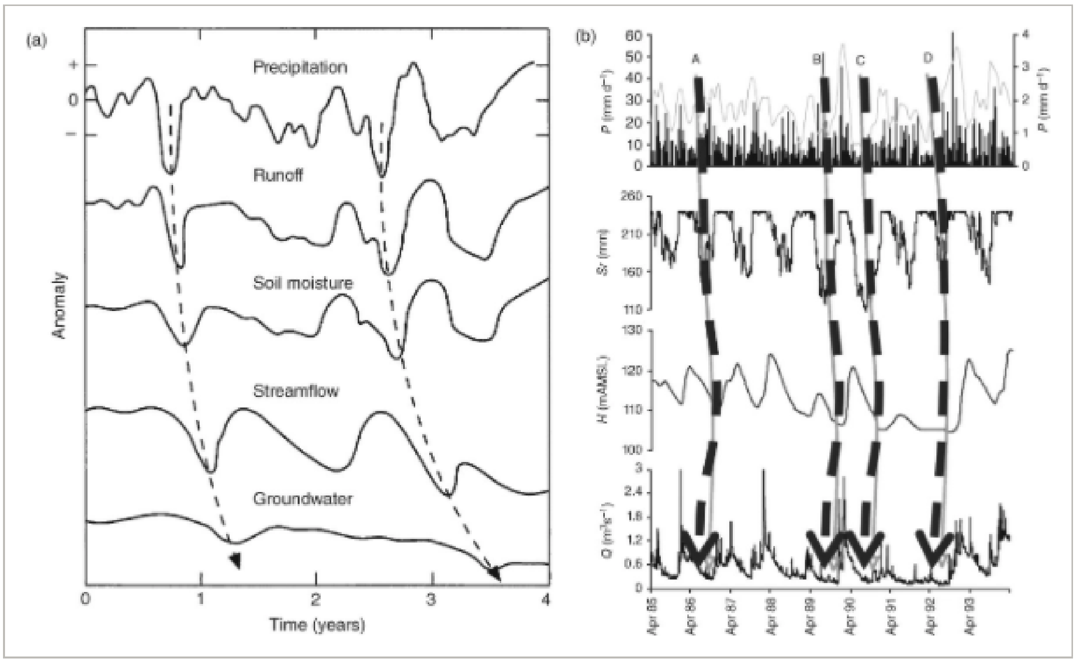


Figure 1. Drought propagation scheme from the atmospheric anomalies to the groundwater ones with runoff drought in a level over soil moisture drought according to Fig. 3. of Van Loon (2015).

The accurate description of drought evolution, which depends on its propagation from one level to the other, may require diving into the processes apart from identifying the effects of drought anomalies at each level. The propagation scheme to follow the evolution of drought described by Van Loon (2015) relies on the monitoring of precipitation, runoff, streamflow, soil moisture and groundwater, which are respectively fluxes and storages that can be easily observed (with the exception of soil moisture). However, early warning and forecasting of drought anomalies at each level requires not only observing the most representative variables of each level (precipitation (flux) of the atmosphere, soil moisture (storage), flow (flux) and water table (storage) of the hydrosphere) but also understanding the interactions between the anomalies of these fluxes and storages related with drought.

One of the frontiers of hydrology consists of the difficulty to determine the interactions between fluxes and storages in the interfaces, especially in the interface between atmosphere and land, which is also called the critical zone and where soil moisture storage is the main player (). The interface between land and atmosphere in the critical zone is particularly challenging, due to the interaction with the biota, which not only refers to the complex response to drought of vegetation (Laio et al., 2001, Vicente-Serrano et al., 2019) and crops (Peña-Gallardo et al., 2019) but also to humans, who proved the most altering (biotic) factor of all (Wanders and Wada, 2015). The following section devotes to the importance of droughts to humans due to its socioeconomic impact.

An additional level of complexity of drought roots from the spatial and temporal scale dependent aspects of the atmospheric, land and hydrologic processes involved in drought. Fig. 2 Shows together examples of spatial (Van Loon, 2015) and temporal scale aspects (Gaona et al., 2021) related to processes involved in drought. Knowing these scale dependencies of the processes, drought is obviously also affected by them, which defines a complex evolution of drought in both the spatial and temporal scales. Drought patterns are at every point of time a combination of the effects of local, regional and global scale factors together with the aspects of precedence, memory and lags at different time scales of the atmospheric-land system.

Multiple studies are focused recently on the quantitative and qualitative characterization of the spatiotemporal evolution of drought (Wu et al., 2016; Li et al., 2020), especially in China, while there are less studies devoted to understand the mechanisms of interactions of the factors involved in the evolution of drought (Huang et al., 2015; Peña-Gallardo et al., 2018).

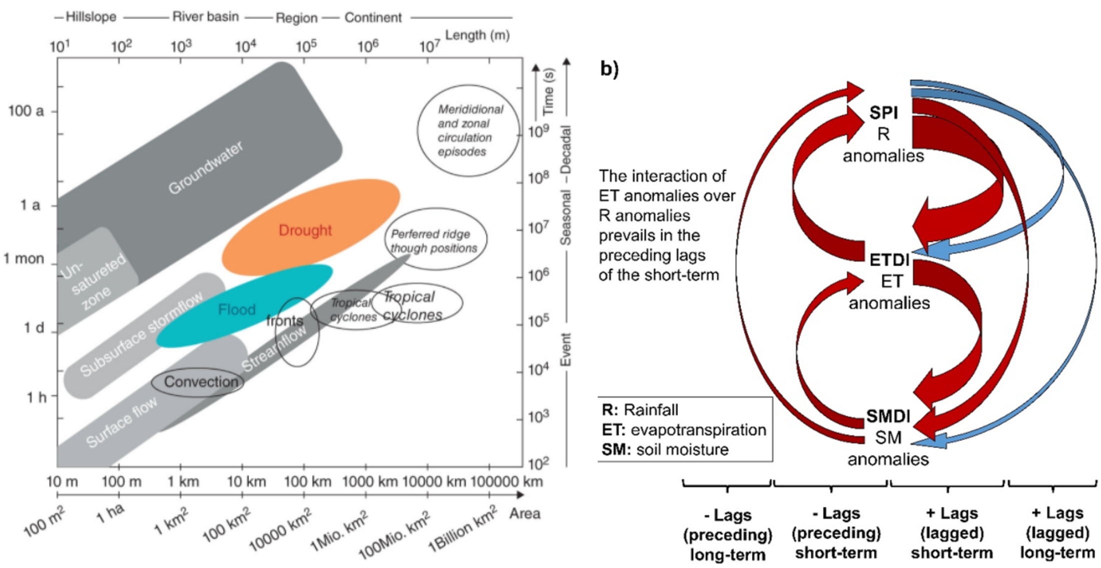


Figure 2. Spatial (Fig. 3 of Van Loon (2015)) and temporal (Fig. 8 of Gaona et al., 2021) scale dependent processes of fluxes and storages involved in the evolution of drought.

The importance of drought due to the impacts and interplay with societies

The relevance of monitoring drought roots from the need to foresee and prevent the impacts of drought in our societies, especially in view of the widespread human impact on the environment (Wilhite, Svovoda and Hayes, 2006; Van Loon et al., 2016a). Historically, meteorological droughts propagated to agricultural or hydrologic droughts undermining the water and food supply of civilizations causing shortages, instability and even their downfall (Von Uexkull et al., 2016; Feitelson and Tubi, 2017; Drysdale et al., 2006). Nowadays, the technical development of our societies ensures a certain degree of resilience against this natural hazard, which does not prevent us from suffering risks or undesired side effects of our water management policies (Baldassare et al., 2019).

Areas where variability dominates the climate are especially prone to drought (Vicente-Serrano and Lopez-Moreno, 2006). This is the case of Mediterranean climates whose characteristic dry season is often the origin of recurring periods of drought (Roberts et al., 2004). The location of the Iberian Peninsula closer than other areas of the Mediterranean basin to the Azores High reinforce the climatic recurrence of drought also beyond the dry season of summer. The Iberian Peninsula is often under the threat of drought (Tejedor et al., 2016) and despite the improvements of resilience to the hazard (Estrela and Sancho, 2016), still faces severe negative socioeconomic consequences on each drought period (Lorenzo-Lacruz et al., 2010; Gil et al., 2013). A typical example of the devastating effects of multiannual droughts is the 1930s Dust Bowl drought in the Great Plains of the USA (Schubert et al., 2004), but there are closer examples in the multiannual Iberian drought of the early 1990s (Llamas, 2000). There is agreement among the scientific community in the need to deepen the analysis of the socioeconomic aspects of drought (Van Loon et al., 2016b).

Impacts, though, do not limit to the socioeconomic consequences and environmental consequences of drought can have long-lasting impact due to the ecosystems when thresholds are trespassed (Asner et al., 2016; Berdugo et al., 2020) leading to complete shifts of food webs (Ledger et al., 2013).

In view of the relevance of drought impacts under steady conditions, and the changes observed in past decades consistent with human influence (Samaniego et al., 2018; Marvel et al., 2019) the recent trends of drought showing events in a path of intensification, increase of duration and shortening of the frequencies are worrisome (Seneviratne et al., 2012; Vicente-Serrano et al., 2014; Pascoa et al., 2017) and prospects considering the effect of climate change look even gloomier (Dai et al., 2011; Spinoni et al., 2018), particularly for the Mediterranean area (Tramblay et al., 2020).

Average annual drought impacts and losses may rise notably within these global warming scenarios, especially in areas like the Iberian Peninsula (Jenkins et al., 2013). These consequences should encourage the peninsular scientific community to allocate more attention to drought both from the interest on the identification, monitoring and characterization of drought but also on its socioeconomic implications.

Tools to study drought: Drought indices

In order to characterize drought, which is essential in both retrospective analysis and prospective planning it is necessary to develop indices able to identify certain features such as the threshold of occurrence, severity, duration and other temporal features and extent and other spatial aspects (Zargar et al., 2011). Drought indicators can be qualitative (merely descriptive) or quantitative (requiring the use of statistical analysis) (Tate & Gustard, 2000).

Several quantitative indices have been developed for the monitoring of different types of drought, especially meteorological, agricultural and hydrological, based on indicator variables such as precipitation, evapotranspiration, soil moisture and runoff (Palmer, 1965; McKee et al., 1993; Narasimhan and Srinivasan, 2005; Bergman, Sabol and Miskus, 1988; Modarres, 2007; Shukla and Wood, 2008).

There are multiple drought indices due to the impossibility to determine with a single indicator the appropriate features of all types of droughts and their consequences to the diverse sectors affected. The handbook of drought indices of the WMO (Svoboda & Fuchs, 2016) indicates that it is advantageous to use different combinations of indexes. This Handbook of indices is a comprehensive and quite updated summary of the indices available for multiple types of drought analysis. The choice of the indices and the suitable combination is necessary to determine which indicators/indices are best suited to the timing, area and type of climate and drought along with the additional applicability aspects to each decision-making scope.

The plethora of indices creates further confusion and recommends using the questions of sensitivity, stability, representativity and applicability to choose the appropriate indices for each purpose. This approach focused on the choice of the optimal indices has a practical perspective while sets aside the need to provide a standard and quantitative definition of drought outside of specific impacts (Lloyd-Hughes et al., 2014).

Types of drought indices included in the Handbook comprise the meteorological, hydrological, soil moisture, remote sensing and composite types of drought indices. Within each of the types Svoboda & Fuchs (2016) identify the input parameters, availability of code, and the complexity of the index definition. This classification is useful when approaching any newly defined index and helps also identify the focus, characteristics, input and output of any index of our interest.

This report summarizes the drought indices used in the Iberian Peninsula following the classification of meteorological, soil moisture, runoff, remote sensing of vegetation and composite/modelled drought indices of the Handbook. We include in the section of each drought index type, a comprehensive summary of the applications in multiple fields of drought research.

Drought indices used in the Iberian Peninsula

Meteorological drought indices

In this section we give an overview of the most relevant meteorological drought indexes based on different main variables such as precipitation and evapotranspiration.

Precipitation

SPI: Standardized Precipitation Index

The Standardized Precipitation Index (SPI) (McKee et al., 1993) is the most used precipitation-based drought index, partially due to the recommendation by the World Meteorological Organization (WMO) as a global measure of meteorological drought (WMO, 2009; Hayes et al., 2011). However, the widespread use of the SPI is due to some advantages: it has a high degree of spatial adaptability to different climatic conditions (e.g., Hayes et al. 1999), it is robust at different time-scales regardless of seasons (Capra and Scicolone 2012), it is spatially comparable (Guttman, 1998), the results are not affected by topography (Lana et al. 2001) and it is not affected by the length of the period used for its calculation (Wu et al. 2005). The SPI involves describing the frequency distribution of precipitation using either a parametric distribution function (McKee et al., 1993) or a nonparametric approach (Hao and AghaKouchak , 2014).

The use of the SPI in the Iberian Peninsula was inaugurated by Lana, Serra and Burgueño (2001) who evaluated the spatial and temporal patterns of monthly rainfall anomalies in Catalonia (NE Spain) using the SPI as a measure of the anomalies. Applying PCA analysis to the spatial database of time series of 30 years of meteorological observations they obtained a regionalization of rainfall anomalies which gives evidence of the climatic diversity of Catalonia between the Pyrenees and the coastal areas while the temporal clustering suggested a decreasing chance of rainfall excess and an increasing affection of rainfall shortages in the territory.

Vicente-Serrano et al. (2004) applied the SPI index to evaluate the spatial and temporal characteristics of drought in the Valencia region. The study demonstrates the convenience of the PCA analysis to differentiate characteristics of drought patterns in the region and to distinguish categories of severity of droughts in the area. Authors highlight the challenge of strong variabilities of drought characteristics at the local scale in the Mediterranean climates.

Vicente-Serrano and López-Moreno (2005) explored the capabilities of the SPI to identify the time scales at which drought affects different components of the hydrological cycle from the rainfall anomalies to the streamflow and reservoir level anomalies. Authors report that reservoir levels correlate best with time scales between 7 to 10 months while streamflow responds to short time scales at the season scale, which can display big seasonal differences.

Soon after, Vicente-Serrano et al. (2005b) assessed the impact of ENSO teleconnection on droughts of the Iberian Peninsula based on the monthly precipitation series of most of the 20th century. Mean values of the SPI-1, -3 ,-6 and -12 months were calculated for each month during El Niño and La Niña years as well as for the year following these events. Results indicate that extreme phases of the ENSO affect the occurrence of droughts in the Iberian Peninsula: significant negative values of SPI tend to occur during the final months of La Niña years and the initial months of the following year more than during the start of El Niño years.

Vicente-Serrano et al., (2006) adopted the Pearson III distribution to adjust the SPI for temporal time scales of 1, 3, 6, 12, 24 and 36 months to identify spatial patterns of drought in Iberia with PCA analysis. Results indicate an increasing number of components with time scale, which indicates great spatial complexity in drought patterns especially in the multiannual scales (24 or 36 months), but the SPI proved able to identify such patterns across regions.

Teleconnections are further explored by López-Moreno and Vicente-Serrano (2008) analyze droughts with the SPI in relation to the NAO index at different time scales for all of Europe over the period 1901–2000. Results show that during the positive/negative phases, negative/positive SPI values are generally recorded in southern Europe, with the opposite pattern recorded in northern Europe but with important seasonal differences. The response of droughts to the NAO is asymmetric, stronger to positive than to negative NAO values. Results also show a strengthening of the influence of the positive phases of the NAO on droughts during the second half of the twentieth century.

Vicente-Serrano (2010) resumed the analysis of drought regional patterns to identify the main drought periods of the XX century using the SPI aggregated at 12 months. The most intense droughts were recorded in the 1940s, 1950s, 1980s and 1990s. The entire Iberian Peninsula tends to fall under drought conditions more frequently than only in a certain region, mostly related to the oceanic influence affecting each of the four regions of a certain type of drought: north, northeast, southeast and central-western areas. Multiple factors such as teleconnections can explain this pattern of regionalization. The study aims to highlight the usefulness of drought regionalization in the context of drought management.

A novel approach to the evaluation of drought was conducted by Santos, Portela and Pulido-Calvo (2012) when they tested the ability of a neural network to hindcast the spring SPI-6, based on winter large-scale climatic indices (teleconnections). Authors explored the link of the spring SPI time series with the winter North Atlantic Oscillation (NAO) and the sea surface temperature (SST) for the period 1910-2004. The winter NAO is a good predictor for the SPI6 of the spring because months of negative NAO tend to display positive rainfall anomalies that propagate into spring months. The north of Portugal is also influenced by SST1 of the Mediterranean Sea while the south are more dependent on winter SST3 (of the North Atlantic between Iberia and North America). Spatial maps of predictive SPI6 for April, May and June were created and validated. Probability maps of the SPI6 values provided by the neural network showed potential to support integrated management of water resources.

The study of Morán-Tejeda et al. (2012) tested the capability of three databases with contrasted spatial resolution to provide SPI estimates for quantifying droughts characteristics like severity and spatio-temporal variability. The low-resolution datasets allow an acceptable measurement of the magnitude, intensity and duration of droughts, while failing mostly in detecting the spatial patterns of the specific drought episodes. Results of low-res SPI proved able for assessing drought impacts on water resources and forest ecosystems.

Long past periods of drought can be inferred in both recurrence and severity in Spain thanks to dendrochronology (Tejedor et al., 2014; Tejedor et al., 2015). These experts on the matter, reconstructed the July SPI-12 from growth variations of 336 samples of tree rings from the province of Teruel generating a SPI-12 series of 318-years. The climate signal contained in this reconstruction is highly significant ($p<0.05$) and spatially robust over the interior areas of Spain located above 1000 meters above sea level (masl). Lower altitude data presented more sensitivity to SPI2 to SPI4. According to our SPI reconstruction, seven substantially dry and five wet periods are identified which comprise 36 drought and 28 pluvial years. Some of the droughts such as 1725, 1741, 1803, and 1879, are consistent with ones from the eastern Mediterranean basin suggesting large-scale synoptic patterns as driving force.

Hindcasting of drought characteristics can be developed from SPI values following the study of Jenkins and Warren (2015). The study, applied over the Iberian Peninsula among other semi-arid areas, aimed to characterize the magnitude, length, spatial extent of drought events to both observed (1955–2003) and projected (2003–2050) precipitation data that are expected to increase in duration and magnitude due to climate change. Results show that on average, droughts increase in duration (SPI12 more than SPI6), magnitude and intensity. Authors highlighted that mitigation measures may be insufficient to cope with drought regimes change, recommending putting the focus on adaptation policies.

The evaluation of the probability of occurrence of drought was firstly attempted by Domínguez-Castro et al. (2018). Authors used both the SPI and the Standardized Precipitation Evapotranspiration Index (SPEI) at 1-, 3-, 6- and 12- month to identify drought characteristics (i.e. duration and severity) and using the extreme value theory obtained drought probability. Results demonstrated the capability of the Generalized Pareto distribution to estimate the frequencies of drought magnitude and duration with important differences in estimations based on the SPI or the SPEI. Results suggest higher probability of extreme drought events in southern and central areas of Spain, compared to northern and eastern regions.

Regarding trends, Vicente-Serrano et al. (2021) generalized the analysis of drought trends of Iberia based on the SPI to western Europe for the period 1851-2018 and indicated that no long-term trends are statistically significant in the drought duration and severity of SPI-3 and SPI-12. Decreasing trends were found in the British Isles and Ireland

The first application of the SPI for agricultural drought analysis was applied by Vicente-Serrano, Cuadrat-Prats and Romo (2006), who combined the SPI index with the AVHRR-NDVI index and crop yield statistics to predict the wheat and barley production in the semi-arid central depression of Ebro Basin with four months in advance. Results show high correlations of SPI and NDVI with crop yields, being the SPI the strongest predictor. The model was able to predict crop yields with notable accuracy in these drought-prone areas of the semi-arid Iberia.

A study with a hydrologic focus on the use of the SPI is the one of López-Moreno et al., (2009). This study examines the effects of a large dam like Alcántara Reservoir on hydrological droughts in the transboundary Tagus River, between Spain and Portugal. Calculating the SPI of monthly stream flows, this paper demonstrates that, as a result of the exploitation of the reservoir, releases in winter and spring are reduced dramatically while the magnitude and duration of summer low flow show a slight increase during dry anomalies. Results identify that streamflow droughts are longer and more intense in the Portuguese part than in the Spanish part than before the construction of the dam.

Pulido-Calvo et al. (2019) also addressed drought temporal characterization in streamflow of the Lower Guadiana Basin, where the river is the border between Spain and Portugal (Algarve-Baixo Alentejo-Andalucía Euroregion). Monthly precipitation time series of Spanish and Portuguese climatic stations with data of the period 1946-2015 were used to calculate the SPI and correlated with streamflow series. Results indicated global cycles of about 25–30 years for severe drought events. Authors suggest the importance of giving priority to the environmental requirements of streamflow in altered basins like Guadiana where water policies are complex.

Research examples purely interested in a specific field of drought are for instance forest studies, which may have the impact of drought on forest growth as their objectives. This is the case of Pasho et al. (2011) who analyzed the impact of drought on the radial growth of eight tree species during the period 1950–2005 growing across a wide climatic gradient in north-eastern Spain. The 1 to 48 months SPI was correlated with ring widths to determine the significant time scale at which drought affected tree growth. Species growing in xeric sites (Pinus, Quercus and Juniperus species) showed the highest responses to SPI time-scales of 9–11 months while more mesic species (Abies alba, Pinus sylvestris) did respond more to SPI time scales shorter than 5 months. Species growing in xeric areas responded to spring-summer SPI while those distributed in mesic sites responded more to summer SPI. The findings have potential to understand forest responses to climate change, especially droughts.

Pasho et al. (2012) resumed the investigation of drought impacts on forest growth focusing on the factors driving growth responses in Mediterranean forests. In this paper, they sampled tree growth of multiple species across a pronounced climatic gradient in NE Iberia and contrasted them with the SPI series. Authors explored a set of abiotic (climate, topography, soil type) and biotic predictors of tree growth (Normalized Difference Vegetation Index, Enhanced Vegetation Index, tree-ring width, diameter at breast height) with two main PCs of corresponding to xeric and mesic sites. Growth responses to drought in xeric forests were mainly driven by the annual precipitation, while in mesic sites the annual water balance was the most important driver.

González-Zamora et al. (2021) explored climatic factors affecting Mediterranean pine (Pinus halepensis) growth together with remotely sensed and modelled soil moisture.
The study was made with a dendrochronological series of 22 forest sites in Spain with different environmental conditions. Correlation of the daily and monthly scales showed that soil moisture was the variable that correlated the most with tree growth and the one that better identified the critical periods for this growth. The maximum correlation coefficients obtained with the rest of the variables were less than half of that obtained for soil moisture. Variability between the sites is mainly modulated by water availability, rather than thermal conditions. These results challenge the traditional focus on evapotranspiration (SPEI) as the main driver of tree growth anomalies during droughts in the Iberian forests.

PCI: Precipitation Concentration Index

The concentration of the rainfall in a year is an important aspect of the climate. An unbalanced distribution of rainfall evokes periods of rainfall excess and periods of drought which make plant and crop growth difficult. Michiels, Grabriels and Hartmann, (1992) proposed the Precipitation Concentration Index (PCI) for characterizing the monthly rainfall distribution, which is a variable assessed for water erosion but could equally inform about certain aspects of interest in drought analysis. Authors in a transect of Central Spain identified that the southern part non-seasonal variability of the concentration of rainfall prevails over the seasonal component. De Luis et al., (2011) applied the PCI and found precipitation in Spain follows a general NW-SE spatial gradient of PCI during the wet (months) period due to the Atlantic storm track, while during the dry (months) period, it follows a predominantly N-S spatial gradient. Autumn is the season with larger PCI variability while winter, spring and summer show more localized patterns. Changes in PCI seem to be complex and appear to be related to global atmospheric features and synoptic and local factors affecting precipitation trends whose anomalies also define drought. More attention might be devoted to this index.

Combined Rainfall + Evapotranspiration

SPEI: Standardized Precipitation Evapotranspiration Index

Vicente-Serrano et al. (2010) designed a new index, the Standardized Precipitation Evaporation Index (SPEI) to combine the sensitivity of the PDSI to changes in evaporative demand with the simplicity of the SPI. The SPEI is based on precipitation and temperature data, and it has the advantage of combining multiscalar capability with the capacity to include the effects of temperature variability on drought assessment. Calculating the index involves a climatic water balance, the accumulation of deficit/surplus at different time scales, and adjustment to a log-logistic probability distribution. Because the SPEI is based on a water balance, it can be compared to the self-calibrated Palmer drought severity index (sc-PDSI). Compared with the SPI and the sc-PDSI indices in different regions of the world, only the sc-PDSI and SPEI identified increases in drought severity associated with higher water demands due to evapotranspiration. Relative to the sc-PDSI, the SPEI has the advantage of being multiscalar.

Vicente-Serrano et al., (2011) tested again the SPEI in comparison with the SPI on the NW Iberian Peninsula from 1930 to 2006 to identify differences between the effects of precipitation variability and warming processes on drought severity and surface water resources. While precipitation increased in the region, PET experienced more increase, which seemed to have increased drought duration by approximately 1 month. No differences in drought severity were observed between the SPI and SPEI. Authors suggest river discharge is mainly driven by precipitation variability, regardless of warming.

A new study comparing SPI and SPEI was conducted by Telesca, Vicente-Serrano and López-Moreno (2012) to investigate the temporal recurrence of droughts in the Ebro basin (Spain) from 1950 to 2006. Results suggest that at the shorter time scales, the signal of SPI and SPEI is characterized by purely random temporal fluctuations. The longer time scales tend to feature the signal as a smoothly varying time series or persistent, mostly due to the aggregation of the indices. Some periodical signals looked common to almost all the sites.

Scaini et al. (2014) compared the capability of L2 Soil Moisture and Ocean Salinity (SMOS) soil moisture product in comparison with SPI and SPEI indices to characterize drought. Authors investigated the potential relationships between the indices and the soil moisture anomalies (SMA) at ten-days scale of both the REMEDHUS (Soil Moisture Measurement Stations Network, Spain) and from the SMOS L2 product. In situ anomalies exhibited higher correlation coefficients with drought indices than those of SMOS, except for the shortest time scale. Remotely sensed anomalies seem to have a high response to precipitation events. The optimal time scale for SMA drought indices was 1 month for the SMOS values and ranged between 30 and 50 days for the in-situ values. Evapotranspiration in the calculation of the indices (SPEI) did not improve the description of the anomalies while soil moisture shows predicting potential.

Vicente-Serrano et al., (2014) assessed the impact of surface relative humidity (RH) and specific humidity (q) in Spain for the period 1961–2011. The subset contained 50 monthly series of RH. Results showed that there was a large decrease in RH, greater in spring and summer, but no overall change in the specific humidity in this period, except in spring, when an increase was observed. The decrease in RH affected Spain entirely, but the changes in specific humidity were less homogeneous. For specific humidity there was a general increase in the northern and eastern parts of Spain, whereas negative trends dominated in the central and southern areas, mainly during the summer months. The results suggest that an increase in the water holding capacity of the atmosphere as a consequence of warming during recent decades has not been accompanied by an increase in the surface water vapor content, probably because the supply of water vapor from the main terrestrial and oceanic areas has been constrained.

Soon after, the authors of the SPEI (Beguería, Vicente-Serrano and Angulo-Martínez, 2010) published a global drought dataset based on the SPEI calculation to provide a gridded product suitable for analysis of drought variability and impacts.

Santiago Beguería et al., (2013) condensed in a new article the computing options to obtain proper estimates of the SPEI. In particular, the log-logistic distribution that enables obtaining standardized values, the methods for computing reference evapotranspiration (ET0), and the procedure to calculate SPEI at different time scales using weighting kernels. Results indicated that the equation used to calculate ET0 can have a significant effect on the SPEI in some regions of the world. Authors recommended the use of unbiased PWM for model fitting. The article additionally provides tools for computation and analysis of SPEI series, an updated global gridded database, and a real-time monitoring system.

Russo et al. (2015) provided the first use of the SPEI for evaluating the role of Circulation Weather Types (CWT) on the spatial and temporal variability of droughts in Iberia. The study aimed to identify the CWT causing droughts in each season over the period 1950-2012. Results show winter tends to be dominated by anticyclonic, east and southeast CWTs which favour drought. SPEI shows a decrease of significant positive correlations with the rain-facilitating CWTs and an increase of the negative correlation CWTs prone to drought. W and SW Iberian Peninsula shows clear negative SPEI-NE CWTs in winter while the Mediterranean experiences positive SPEI-NE CWT in summer. THE SPEI correlates positively to W, SW, NW CWTs in winter. The winter droughts are associated mainly with high frequency of E types and low frequency of W CWTs types for all areas, while the summer drought in eastern sectors are linked with low cyclonic frequency, as well as the western regions are related with the N type.

Vicente-Serrano et al. (2015) further explored the role of weather patterns across Europe by analysis the influence of the North Atlantic Oscillation (NAO), the East Atlantic (EA), the Scandinavian (SCAN) and the East Atlantic–Western Russia (EA–WR) and the Esterly Index (WI) on SPEI series. Results indicated that European drought variability is better explained by the station-based NAO index and the WI than by any other combination of circulation indices. In northern and central Europe the variability of drought severity for different seasons and time-scales is strongly associated with the WI. On the contrary, the influence of the NAO on southern Europe droughts is stronger. Lagged correlations of the NAO and WI with the SPEI have potential to anticipate drought severity.

Peña-Gallardo et al., (2016) incorporated the use of the Standardized Drought Precipitation Index (IESP) to the comparison of SPI and SPEI to evaluate the changes on drought over the period 1901-2012 in Andalucía region. Results showed that not all the indices respond similarly identifying the intensity and duration of dry periods in this kind of region where geographical and climatic variability is one of the main elements to be considered.

Studies using the SPEI with an agricultural scope include the one of Páscoa et al., 2016 who first assesses the production of wheat in the Iberian Peninsula in relation to interannual changes in precipitation and long-term trends of both rainfall and evapotranspiration. Works from the same authors identified trends in precipitation and temperature, so this study focuses on the evaluation of the impacts on wheat yield by drought for two sub periods (1929–1985 and 1986–2012). The results show that in western areas, wheat yield is positively affected by dryer conditions, whereas the opposite happens in eastern areas. The winter months have a bigger influence in the west while the east is more dependent on the spring and summer months. Results indicate that May and June have a strong control on wheat yield. Authors also note the increase in areas with positive correlation and the decrease in areas with negative correlation between wheat yields and SPEI, probably due to the increase of dry events.

Páscoa et al., (2017) assessed the long-term trends in drought over the Iberian Peninsula over 112 years comparing SPEI and SPI. Results of both indices show trends in duration, magnitude and intensity of droughts related to the positive trend of precipitation of the northwest, and the negative trends of the south. The SPEI differs from SPI in displaying larger areas affected by drought which agrees with the evapotranspiration upward trend due to rising temperatures.

Coll, Aguilar & Ashcroft (2017) adopted again the comparison of SPI and SPEI at annual and seasonal scale to analyze trends of droughts in Iberia over more than 100 years of precipitation and temperature datasets. Results confirmed the increase in temperatures and the non-significant trends in precipitation. Indices performed very similarly, although the SPEI showed greater drought severity and larger surface area affected. Moreover, a clear drying trend was found by the SPEI for most of the Iberian Peninsula at annual scale and also for spring and summer, although the SPI did not experience significant changes in drought conditions. Results are in agreement with those of Vicente-Serrano et al., (2011).

González-Hidalgo et al. (2017) also adopted the popular comparison of SPI and SPEI (at 12, 24, and 36 months of aggregation) but with the purpose to analyze the spatial propagation of drought conditions between 1961 and 2014 in Iberia. During the first half of the period, the SPI usually returned a higher identification of drought areas, while the reverse was true from the 1990s, suggesting that the effect from atmospheric evaporative demand could have increased. Regarding temporal propagation, no straightforward rule of time lag was found due to the overlap effects in time and space. Spatially, the propagation of drought events affecting more than 25% of the total land indicates the existence of various spatial gradients of drought propagation, mostly east–west or west–east, but also north–south have been found. No generalized episodes were found with a radial pattern, i.e., from inland to the coast.

García-Valdecasas et al., 2017 evaluated the capability of the Weather Research and Forecasting (WRF) model to generate downscaled fields suitable for the detection of dry periods over Spain. The SPI and SPEI indices computed at 3- and 12-month time scales from the WRF model were compared with the ones obtained from the MOPREDAS, MOTEDAS and ERA-Interim databases. Results show the WRF provides estimates of the drought indices that largely improved those of ERA-interim, but greater for SPI than SPEI, and in longer time-scales. Other variables of drought such as the intensity of drought estimated with WRF improve more in comparison with observations than to databases.

High-spatial-resolution probability maps of drought duration and magnitude across Spain

Domínguez-Castro et al. (2018) is a second study aiming to characterize drought with a probabilistic scope. SPI and SPEI indices are used to map drought probability using the extreme value theory. This method proposes thresholds to define drought duration and magnitude. Results show a good performance of the generalized Pareto distribution (GP) for estimating frequencies of drought magnitude and duration. The model data compares well with the observations and reveals patterns of higher probability of extreme drought in southern and central Spain compared to the northern and eastern regions, while there are differences between the SPI and SPEI.

The same author, Domínguez-Castro, et al. (2019) expanded the study of drought events in Iberia and the Balearic Islands with the SPI and SPEI to characterize the spatial and temporal variability of the frequency, duration and magnitude of droughts. Results show more frequency of droughts in the north than in the south, while the average duration and magnitude of the drought events in central and southwestern regions duplicate those recorded in northern areas. The comparison of indices show SPEI indicates higher drought durations and magnitudes at 1-, 3- and 6-months timescales. Results also indicated a nonsignificant tendency toward higher drought duration and magnitude over Spain.

Manzano et al (2019) resumed the interest in teleconnections and evaluated the SPEI at 3-months' time scale with the North Atlantic Oscillation (NAO), Arctic Oscillation (AO) and Western Mediterranean Oscillation (WeMO) over Iberia. The authors performed a wavelet analysis to the seasonal mean atmospheric pattern time series and clustered mean SPEI time series to identify the periodicity features of relationships between the atmospheric patterns and the drought index. Results show the SPEI mostly correlated with the Arctic and North

García-Herrera et al. (2019) analyzed the record-breaking drought that affected western and central Europe from July 2016 to June 2017, which caused widespread impacts, due to its unusual spatial pattern affecting both northern and southern European regions. Authors used both SPI and SPEI for the characterization of drought and the factors forcing it. The consecutive occurrence of blocking and subtropical ridges led to latitudinal shifts of the jet stream and record-breaking positive geopotential height anomalies over the continent. The reduction in moisture transport from the Atlantic was relevant in the northern part of the region causing decreased precipitation and increased sunshine duration. High temperatures and the resulting increase in atmospheric evaporative demand, were more important in the south. Results indicate that this type of drought may occur more frequently in the future.

Russo et al., (2019) proposed a novel use of the comparison of SPI and SPEI. They aimed to analyze if spring and early summer drought cause the occurrence of extremely hot days/nights in the Mediterranean basin. Authors correlated the number of hot days (NHD) and nights (NHN) in the region's hottest months with SPI and SPEI at 3-, 6- and 9-months of time scale, between 1980 and 2014. Most regions exhibit statistically significant negative correlations, i.e. high (low) NHD/NHN following negative (positive) SPEI/SPI values, and thus a potential for NHD/NHN early warning. Ribeiro et al. (2020) continued with this scope by analyzing the joint probability distribution (copula theory) of extremely hot summer days in the Iberian Peninsula (IP) being preceded by drought events in spring and early summer. Authors identified a non-linear dependence between SPEI and NHD was very well identified for the most of the IP's regions by asymmetrical copulas with upper tail dependence (except in northwestern regions), suggesting that compound hot and dry extremes are strongly associated. Results show more probability of exceeding summer NHD values after the transition from wet to dry weather.

The recent availability of high-resolution climatic databases such as the Iberia01 used by Páscoa et al., (2021) allows for the identification of drought patterns with finer temporal and spatial scales. Authors assessed drought in Iberia using both the SPEI and SPI for the period 1971–2015, with 0.1° horizontal resolution. Results indicate a clear drying trend in most of Iberia is identified with both indices and both datasets in drought duration, but not in drought intensity that decreases slightly. The improved resolution of datasets such as the one of Iberia01 allows to identify more complex patterns of drought trends.

Liberato et al. (2021) proposed the ranking of the persistent drought and wet events identified with the SPEI index over Iberia in the period 1901-2016 by means of a log-logistic probability distribution function. The ranking classification method is based on the assessment of the magnitude of an event, considering both the area affected and its intensity in each grid point. Authors develop a dataset with the rankings of the most extreme, prolonged, widespread dry and wet periods in the Iberian Peninsula at timescales of 6, 12, 18, and 24 months. Results show that no region in the Iberian Peninsula is more prone to the occurrence of any of these long-term (dry and/or wet) extreme events.

García-Valdecasas Ojeda et al. (2021) resumed the use of the WRF model to evaluate droughts, in this case considering the RCP4.5 and 8.5 climate change scenarios, whose temperature rise could play a key role in changing drought characteristics. Drought were examined in terms of duration, frequency, and severity of drought events. The WRF model was driven by two flocal climate models, the CCSM4 and the MPI-ESM-LR, for a near (2021–2050) and a far (2071–2100) future. Changes were analyzed using the SPI and the SPEI index at different time scales (3- and 12-months). Results by both indices showed that Iberia is going to undergo longer and more severe drought events with sharp changes on frequency, severity, and especially in the case of duration, in particular under the RCP8.5 scenario. Projected drought conditions using the SPEI showed more severe increases in drought events than the SPI. The overall results suggest a significant risk of megadrought by the end of the century.

There are not many applications of the SPEI with a purely hydrological scope, such as on the assessment of streamflow and reservoirs. The following two are the best examples.

A comparison of SPEI with SPI index with a hydrological focus was provided by Lorenzo-Lacruz et al. (2010), who assessed the influence of climate variation on the availability of water resources in the upper Tagus River basin. Both indices confirmed that drought conditions have prevailed in the headwaters of the Tagus River since the 1970s. The responses in river discharge and reservoir storage were slightly higher when based on the SPEI rather than the SPI, indicating that although precipitation variability dominates the influence of temperature was not negligible. Moreover, the greatest response in hydrological variables was evident over longer timescales of the climatic drought indices but also related to complex regulation-demand issues. The water availability in the basin is experiencing more frequent droughts, in contrast with the amount of water transferred, which shows a clear upward trend due to demands.

Vicente-Serrano et al. (2014a) addressed again the study of hydrologic drought in the entire Iberian Peninsula with SPI and SPEI finding that drought severity increased in the past five decades, as a consequence of greater atmospheric evaporative demand resulting from temperature rise. Results suggest the increase in drought severity is independent of the evapotranspiration. By analyzing streamflow data for 287 rivers in the IP authors found that hydrological drought frequency and severity increased in the past five decades, which suggest that positive trends in the atmospheric water demand had a direct influence on the temporal evolution of streamflow, especially in warm seasons.

Multiple studies of forest research used the SPEI as an index to identify the periods of drought affecting Iberian forests. Camarero et al., (2013) inaugurated the study of the impact of droughts in forest with the SPEI. The dendrochronological series comprise records of Pinus nigra along a gradient of aridity which is compared to the SPEI series and the North Atlantic and Western Mediterranean Oscillation indices. Wet and cold previous autumns and warm late winters enhance tree growth. Growth was significantly related to North Atlantic and Western Mediterranean Oscillations in two out of five sites while the strongest responses of growth to the drought index were observed in the most xeric sites.

Martin-Benito, Beeckman & Cañellas, (2013) also investigated the influence of climate on the ring width and xylem anatomy of Pinus nigra Arn. But included P. sylvestris L. in the analysis of tree ring growth in relation to drought. Dendrochronological series include ring width, mean lumen diameter and mean cell-wall thickness and the number of cells between 1960 and 2006. Results showed that periods of drought were the main climatic driver of tree radial growth, although trees were also sensitive to temperature (negative effect in previous autumn and current summer) and precipitation (with a general positive effect). P. sylvestris response was stronger to the climate of the current year, whereas the effect of previous-year climate was more important for P. nigra. Warm and dry summers reduced all variables in both species, whereas warm winter-spring temperatures favour growth, especially in Pinus sylvestris. Previous-year or early-season conditions mainly affected earlywood features, whereas latewood was more responsive to summer. Drought affects cell-wall thickness while lumen width increases in the latewood of P. sylvestris. Anatomical variables record different and stronger climate information than ring width, especially in P. sylvestris. SPEI-3 months series is generated based on these variables, more accurate than only tree ring growth, or climate reconstruction.

Vicente-Serrano, Camarero and Azorín-Molina, (2014) continued with the application of the SPEI in comparison with tree-ring records and to determine if relations are influenced by climate type and forest features. Data used is the dendrochronological series of thousands of trees with the information on precipitation and temperature variability required to calculate the SPEI in such locations. PCA analysis helps to identify the contribution of various environmental factors to the correlation between SPEI and tree rings. Results show the period between the water shortage and the impact on tree growth differs among forest types and tree families. Authors identified a gradient in the response of growth to drought including: (1) forests that do not respond to drought, such as those located in cold and very humid areas; (2) forests located in semi-arid areas characterized by responses to long-term droughts; (3) forests that respond to medium- to long-term droughts subjected to sub humid conditions; and (4) forests that dominate humid sites and respond to short-term droughts.

A slightly different perspective on forest-drought interactions focus on the role of drought on wildfire occurrence. Russo et al. (2017) investigated the impact of drought periods on burned areas in Iberia. Comparing time series of SPI and SPEI with the time series of the standardized logarithm of normalized burned areas during the fire summer season, authors reveal that the association between drought and fires is a local scale process; and that the relation between wildfires and drought is very influenced by the spring precipitation more than by temperature and precipitation during summer on most of the Portuguese provinces. Results also highlight the strong relation between short timescales of drought and burned areas, especially in western Iberia, while there is some lag in central and eastern Iberia.

Other factors of interest in forest research can also be tested from a drought perspective. Oliveira, Lauw & Pereira, 2016 studied the impact of drought on the growth of cork in Cork oaks (Q. suber) of the Mediterranean region. Authors evaluated the sensitivity of cork growth to extreme drought events using a 24-year chronology (1986–2009) including important droughts. The series of cork growth are compared with the SPEI index at different time scales (1-24months) to find the most influential time scale. Results show cork growth as very sensitive to the strong droughts of the 90s and good recovery after them, revealing resilience. Cork growth showed high responsiveness and sensitivity to later spring precipitation, 2-12 mo.

The resilience of mediterranean pine species to droughts was again the focus of Rodriguez-Vallejo and Navarro-Cerrillo (2019), who used the SPEI together with dendrochronological data to assess the response to drought in natural and planted forests of Pinus pinaster in the south of Spain, especially regarding how environmental variables drive radial growth. Results showed contrasting growth responses to drought between natural and planted stands, but with non-significant differences after repeated drought periods. The SPEI of 12-month temporal scale identified the importance of spring precipitation and the mean temperature in late winter on growth. Similar results were obtained for other pine species before (Martin-Benito, Beeckman & Cañellas, (2013)).

The resilience of non-mediterranean forest species to droughts has been also explored. Serra-Maluquer et al. (2019) investigated if the growth decrease of Fagus sylvatica observed in Iberia
is related to global warming and drought. Authors samples of beech forests (215 trees) across four climatically contrasting regions (Mediterranean, Pyrenean, low- and high-elevation Atlantic areas) near the southern distribution limit of the species using their dendrochronological series to quantify the changes in tree ring growth from the 1950s in comparison with the meteorological series classified with the SPEI. Results show a decline of growth in most areas, especially those most exposed to drought, but differences occur regionally which did not seem warming-related. Pyrenean beeches may benefit from warming while Atlantic and Mediterranean forests may see increases in growth declines due to drought.

Further studies focus on the interaction of drought and frosts on tree radial growth (Gazol et al., 2019). Authors stated climate warming also affects the growing season altering the periods of tree growth which may become affected by frosts in spring and drought in summer. Using tree ring growth databases in relation to the climatic variables quantified by SPEI-18 months in August, authors evaluate frost and drought effects on Fagus sylvatica and Abies alba for the period 1950–2012. Results show growth of European beech and Silver fir was reduced by the occurrence of both late frost events and summer drought, but no interaction was found between both factors. Beech was more negatively impacted by late frosts, whereas Silver fir was more impacted by summer drought.

Other authors focus on the evaluation of the impact of forest management measures in the resilience of the forest to drought. Manrique-Alba et al., 2019 evaluate the impact of thinning forests on drought resilience since many dense forests may suffer just due to tree-to-tree competition for soil water. Authors combined dendrochronology and C and O isotope analyses of wood in two Aleppo pine (Pinus halepensis) plantations, growing under semiarid conditions and experimentally thinned at high and moderate intensities along with control. The main aim was to understand the responses of radial growth and water use efficiency (WUEi) to different thinning intensities, and to analyze the effectiveness of thinning to enhance growth resilience after the drought periods identified by the SPEI index. Results show thinning had a positive effect reducing growth sensitivity to drought and the effects of thinning remained for long.

A recent article adopted a combined climatological-forester scope, using SPEI and dendrochronological data to investigate the role of teleconnections on tree growth (Casas-Gómez, 2020). This study used the SPEI, as a reliable indicator of drought, to investigate the drought sensitivity to the NAO and Westerly Index of tree-ring width TRW data long-lived conifers of the Mediterranean basin (Abies borisii-regis, Abies cilicica, Abies pinsapo, Cedrus atlantica, Cedrus libanii, Pinus nigra, Pinus heldreichii). Results show that NAO and WI relations with TRW present contrasting Mediterranean dipole patterns regarding drought sensitivity to tree growth. Both NAO and WI had stronger correlations in the West of the basin with SPEI and

TRW. Authors remark the potential of TRW as a feasible proxy to long-term reconstructions of Westerly Index (WI) variability in the Western Mediterranean region. Spatial variability of drought suggested a dipole-like complex relation between NAO and WI across the basin.

RDI: Reconnaissance Drought Index

The Reconnaissance Drought Index (RDI) developed by Tsakiris and Vangelis (2005) is defined as the ratio of the aggregated precipitation and PET. The P /PET ratio is also an aridity index and can be standardized for cross comparison with other drought indicators. The RDI is different from the other indices in the sense that it does not use the actual ET but PET estimates derived from satellite-retrieved data, which is a simplistic assumption given many meteorological variables including net radiation, wind speed, and relative humidity affect PET rates (McVicar et al., 2012).

Only one application of the RDI is available in the Iberian Peninsula. Vicente-Serrano et al. (2015) analyzed the sensitivity of four drought indices, SPEI, PDSI, Standard Drought Palmer Index SPDI and the RDI, to precipitation and reference evapotranspiration (ETo) inputs. The study uses observational data with different variabilities across different regions of the world for the intercomparison of the indices. Results show differences in the sensitivity to ETo and P among the four drought indices. PDSI showed the least sensitivity to variation in their climate inputs. The RDI was only sensitive to the variance but not to the average of P and ETo. The SPEI shows the largest sensitivity to ETo variation, with clear geographic patterns mainly controlled by aridity. The low sensitivity of the PDSI to ETo makes the PDSI the suitable drought index in applications in which the changes in ETo are most relevant. Conversely, the SPEI shows equal sensitivity to P and ETo. This study was the root of the widespread use of the SPEI in Iberia where important ETo changes have occurred in recent decades.

Evapotranspiration

The study of evapotranspiration in reference to drought in Iberia was inspired by Vicente-Serrano et al. thanks to their studies on the matter and the development of the SPEI index which includes the effect of evapotranspiration changes on drought identification.

These authors (Vicente-Serrano et al., 2014d) also provided a relevant dedicated analysis of the trends of reference evapotranspiration (ET0) in the Iberian Peninsula for the period from 1961 to 2011. Twelve methods were analyzed to quantify ET0, some of them temperature based (e.g., Thornthwaite, Hargreaves, Linacre), whereas others requiring additional variables (e.g., Priestley–Taylor, Papadakis, FAO–Blaney–Criddle). The Penman–Monteith equation was used to compare ET0 among the methods. At annual and seasonal scales some of the ET0 methods requiring only temperature data for calculation provided better results than more complex methods requiring more variables (except for Penman-Monteith). Among them the Hargreaves (HG) equation provided the best results. The analysis of the temporal variability and trends in the magnitude of ET0 indicated that all methods show a marked increase in ET0 at the seasonal and annual time scales. Nevertheless, results obtained suggested substantial uncertainties among the methods assessed to determine ET0 changes when considering temperature changes. ET0 trends obtained by methods that only require temperature should be evaluated carefully under the current global warming scenario.

Several drought indicators have been developed to integrate ET as a variable of interest for drought analysis (AghaKouchak et al., 2015) such as the Crop Water Stress Index (CWSI) (Jackson et al., 1981), the Evapotranspiration Deficit Index (ETDI) (Narasimhan and Srinivasan, 2005), Evaporative Stress Index (ESI) (Anderson et al., 2011a), Evaporative Drought Index (EDI) (Yao et al., 2010) and the Evaporative Demand Drought Index (EEDI) (Hobbins et al., 2016). However, only a few of them have been applied in the Iberian Peninsula, partially due to the widespread use of the SPEI, which considers the effect of evapotranspiration but does not provide the same information as dedicated evapotranspiration indexes like the ones above.

Consequently, this section includes the only application of evapotranspiration-dedicated indices in recent years in Iberia, the contribution of Pablos et al, (2017, 2018) using AWD with other agricultural indexes and (Gaona et al., 2021, in review).

Atmospheric water demand

Pablos et al, (2018) showed that the AWD Index provides appropriate support to the characterization of soil moisture drought in comparison with the SMADI, SWDI and the CMI, despite its atmospheric nature.

ETDI: EvapoTranspiration Deficit Index

The second index is the EvapoTranspiration Deficit Index (ETDI) defined by Narasimhan and Srinivasan (2005). The first step for calculating this index implies defining water stress ratio (WS) for the desired time step (i.e. week/month), which is the difference of potential evapotranspiration (PET) with actual evapotranspiration (AET) divided by PET. The average of this water stress ratio WS is used to obtain the median, maximum and minimum values of each week/month-year of the time series. These long-term median, maximum and minimum water stress ratios then lead to the weekly/monthly percentage of water stress anomaly (WSA):

$$WSA_{i,j} = \frac{WS_{i,j} - MWS_j}{MWS_j - minWS_j} x100, \quad if\ WS_{i,j} \le MWS_j$$

$$WSA_{i,j} = \frac{WS_{i,j} - MWS_j}{maxWS_j - MWS_j} x100, \quad if\ WS_{i,j} > MWS_j$$

The seasonality is removed operating the equations above where the water stress anomaly (%) $WSA_{i,j}$ is obtained dividing the difference of water stress of the week/month $WS_{i,j}$ with the median value of the period MWS_j by the negative ($MWS_j - minWS_j$) or positive range (max $WS_j - MWS_j$) of water stress values registered for that week/month-year of the time series. WSA ranges from -100 to 100 to indicate periods of limited evapotranspiration to periods of unrestricted ET. To become a non-seasonal index suitable for comparing time series of diverse climatic characteristics at different accumulation periods, the ETDI is defined by the accumulation of WSA along the series of j time steps.

$$ETDI_j = 0.5\ ETDI_{j-1} + \frac{WSA_j}{50}$$

The only example of the application of the ETDI index is the work of Gaona et al. (2021, in review), who adopted this index together with the SMDI index from the same authors (Narasimhan and Srinivasan, 2005) and the SPI to investigate the temporal relations between anomalies in the three main levels of drought in the atmospheric-land system: anomalies of precipitation (SPI), evapotranspiration (ETDI) and soil moisture (SMDI). The lag analysis used in this study identifies the existence of multiple precedence patterns of interaction between the anomalies of these variables, particularly of evapotranspiration over precipitation and soil moisture. These results support the concept of drought onset as an overlay of interacting anomalies of different potential of action, being evapotranspiration the most powerful factor in semi-arid climates such as the ones of the Mediterranean basin, where long high-energy periods prevail.

Soil Moisture drought indices

Soil moisture anomalies can inform about the evolution of a crucial variable of the surface that interacts with many other processes propagating drought from the meteorological to the land and hydrological levels of drought.

SWDI: Soil water deficit index

Martínez-et al. (2015a) first proposed the use of the Soil Water Deficit Index (SWDI) as an index for agricultural drought monitoring using the increasingly available soil moisture observation databases and remote sensing data. The definition of the SWDI is simple based on the field capacity and wilting point, which can be obtained from observations of pedotransfer functions. Authors applied the SWDI in an agricultural area where Salamanca University maintains a large soil moisture observation network. Results of the SWDI presented good results at both daily and weekly time scales when compared to two climatic water deficit indicators and agricultural production. The parameters needed for the index can be easily obtained from long-term soil water series. The long-term minimum, the growing season minimum and the 5th percentile of the soil moisture series seemed good estimators for the WP. The min of the max value of the growing season is the best estimator for FC.

Martínez-Fernández et al. (2015b) expanded the characterization of soil anomalies with the Soil water deficit index (SWDI) from observations and SMOS remote sensing data for agricultural drought monitoring in comparison with other soil moisture and evapotranspiration indices. Authors identify a knowledge gap in that soil moisture is the main variable evaluated for agricultural drought, while the actual soil water content may be more informative but is rarely taken into account in the study of drought. In this work, the SWDI was calculated using the SMOS and REMEDHUS data (Soil Moisture Measurement Stations Network of University of Salamanca) during the period 2010–2014. In this work, the SWDI was calculated using the SMOS data in the REMEDHUS area for the period 2010–2014. The satellite SWDI was calculated using several sets of soil water parameters and was compared with the SWDI obtained from in situ data. A first approach to define the deficit was proposed using the 5th percentile as an estimator for wilting point and the 95th percentile and the minimum of the maximum value during the growing season as estimators for field capacity. Results with this approach were good, but the temporal distribution and the range were unrealistic. Other approaches were based on in situ data parameters and pedotransfer functions estimation. In this case, results were better, and the satellite data adequately identified drought dynamics. Finally, SMOS SWDI compared well to the Crop Moisture Index, CMI, and the Atmospheric Water Deficit, AWD, which proved that SMOS SWDI reproduces well soil water dynamics.

Martínez-Fernández et al. (2017) further explored the suitability of the SWDI index obtained from observations in comparison with the CCI soil moisture product form the ESA climate change initiative over an area of Zamora province from 1978 to 2014. The results of SWDI with CCI were also compared with those obtained with two soil moisture products from the Soil Moisture and Ocean Salinity (SMOS) satellite. The results obtained were very promising and paved the way for using CCI database as a long-term soil moisture database useful for agricultural drought monitoring.

From the same group, Almendra-Martín et al., (2020), explored the drought trends over the past four decades on the Iberian Peninsula using the SWDI. In this case, authors used two different soil moisture databases (Lisflood and ERA5-Land) to perform the analysis at daily and weekly temporal scales. Climate characteristics and soil properties were also considered to detect their influence on the trends and spatial patterns. Results showed a clear dominance of negative trends over a 10-month period that coincided with the growing season of most of the crops on the IP, while a positive trend was observed over 2 months. No differences were found based on the climatic zone or soil characteristics. However, clay content seemed to mitigate or lag the negative trends.

SMADI: Soil Moisture Agricultural Drought Index

Sanchez et al. (2016) explored the potential of combining SMOS and MODIS analysis for drought monitoring with an agricultural scope using a new index: the Soil Moisture Agricultural Drought Index (SMADI). The SMADI Index aimed to combine soil moisture and temperature conditions including the lag of vegetation to changes in the conditions. Regarding the data used, the SMADI integrates the surface temperature (LST) and NDVI from MODIS and the soil moisture observations from the SMOS mission to explore inverse relations between variables. The study evaluates the performance of the SMADI Index in comparison with other common drought indices used in the Iberian Peninsula such as the SPI, CMI and the SWDI. The best SMADI version was the one combining SMOS data with the daily LST and NDVI of MODIS. SMADI agrees to a great extent with the CMI and SWDI indices and a bit less with the SPI at the local scale of the REMEDHUS area but loses agreement with the increasing spatial scale. Despite these differences, SMADI was anyway able to capture the duration and intensity of the drought events. The NDVI proxy seems to support the surface limitations from SMOS data while capturing part of the delayed vegetation response to soil moisture changes. This occurs when SMADI index downscales the SMOS coarse spatial resolution (20km) to the resolution of MODIS (500m) which increases its suitability for practical applications. The study highlights the synergies between the optical and microwave remote sensing data for drought monitoring.

Sánchez et al. (2018) further explored the capabilities of the SMADI index as a global estimator of agricultural drought. The period of the study spanned from 2010 to 2015. Three spatial scales (local, regional and global) were used to compare the agricultural drought events captured by SMADI against existing agricultural drought indices, as well as reported occurrences of drought events from dedicated databases. Results show that SMADI had good consistency with two agricultural indices in the center of the Iberian Peninsula at the local and regional scales, depicting 2012 and 2014 as the driest years in the area. A comparison of SMADI across the United States of America with the impact and intensity maps of drought from the US Drought Monitor (USDM) revealed a reasonable match with the temporal and spatial extent of the affected areas, detecting the most intense drought events. Finally, a comparison at the global scale with documented events of drought world-wide showed that SMADI was able to recognize more than 80% of these events for more than 50% of their duration. Thus, authors highlight the advantages of SMADI, whose calculation is simple and fast, relies on data that are readily available, thereby providing a rapid overview of drought-prone conditions that could enhance the present capabilities of early warning systems.

SWeTDI: Soil Wetness Deficit Index

Pablos et al. (2017) adopted the use of the Soil Water Deficit Index (SWDI), the Soil Wetness Deficit Index (SWeTDI) and the Soil Moisture Deficit Index (SMDI) apart from the SMADI to evaluate agricultural drought characterization over semi-arid crop regions of the Duero basin.
Authors computed the indices on a weekly basis from June 2010 to December 2016 using 1-km satellite SM estimations from SMOS and/or MODIS data. The temporal dynamics of the indices were compared to two well-known agricultural drought indices, the atmospheric water deficit (AWD) and the crop moisture index (CMI), to analyze the levels of similarity, correlation, seasonality and number of weeks with drought. In addition, the spatial distribution and intensities of the indices were assessed under dry and wet SM conditions at the beginning of the growing season. The results showed that the SWDI and SMADI were the appropriate indices for developing an efficient drought monitoring system, with higher significant correlation coefficients ($R \approx 0.5$–0.8) when comparing with the AWD and CMI, whereas lower values ($R \leq 0.3$) were obtained for the SMDI and SWetDI.

SWI: Soil Water Index

Pablos et al. (2018) used the SWI to compare the methods for root zone soil moisture (RZSM) estimation using the Soil Moisture Active Passive (SMAP), the SMOS L4 RZSM, the SMOS-Barcelona Expert Center (BEC) L4 SSM product and the apparent thermal inertia (ATI)-derived SSM from MODIS data. The temporal estimates of the RZSM were compared to in situ RZSM from 14 stations of REMEDHUS area. Spatial assessment was conducted comparing RZSM maps between the different RS data product estimates. All RZSM values followed the temporal evolution of the ground-based measurements well, although SMOS and MODIS showed underestimation while SMAP displayed overestimation. The good results obtained from MODIS ATI are notable. A very high agreement was found in terms of spatial patterns for the whole Iberian Peninsula except for the North mountains and coast.

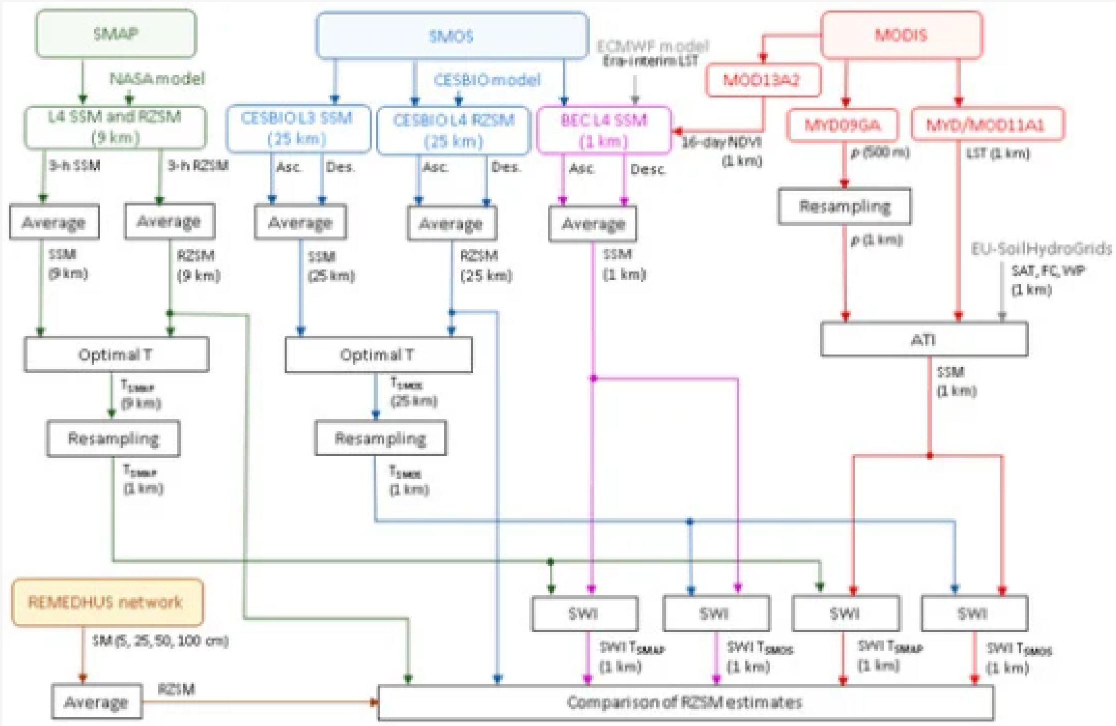


Figure 1

Fig. 3: Workflow of the comparison of products with the SWI index for RZSM estimation (Pablos et al., 2018)

<u>SMDI: Soil Moisture Deficit Index</u>

The SMDI is the twin index of the ETDI developed by the same authors (Narasimhan and Srinivasan, 2005). The calculation of the index follows the same procedure indicated in the section of the evapotranspiration index ETDI.

The study of Pablos et al. (2017) indicated the advantages and disadvantages of the Index for agricultural drought monitoring. Its standardized nature is advantageous to fade away the effect of seasonality but can also be a disadvantage when such seasonality is of interest for the analysis. Authors outline its accuracy in the identification of the periods of drought, very close to that of SMADI and SWeTDI, while indicate that its limitations with variability are probably related to the need of long-term series to calculate the maximum, minimum and median values of anomalies required for the definition of the index.

Apart from the study of Pablos et al. (2017), only one more study (Gaona et al., 2021, in review) adopted the use of the SMDI as a dedicated index for the monitoring of drought in soil moisture. Description of the study in the ETDI index section devoted to evapotranspiration-dedicated indexes already indicated that authors were interested in separating the effects of the anomalies of relevant variables in the development of drought such as precipitation, evapotranspiration (investigated through the ETDI) and soil moisture, whose anomalies were studied with the SMDI. The SMDI Index in this study provided insightful information about the capabilities of soil moisture anomalies to control and lag the propagation of drought from the atmospheric levels (precipitation and evapotranspiration) to the land-surface.

Hydrological drought indices

Few studies using drought indices have a hydrologic scope in the Iberian Peninsula. This scarcity of research in the hydrological impact of drought is certainly surprising given the importance of streamflows, reservoir storage and piezometry in supporting water use of the highly regulated Iberian basins.

Martone index

Fernández et al., (2009) used the Martone index as an explanatory variable of hydrological drought in Galicia. The stochastic behavior of the drought events was reproduced applying a multiplicative seasonal autoregressive integrated moving average model. The forecast analysis comprised the 12 leading months of streamflow, with three drought thresholds: streamflow means, monthly streamflow mean and standardized streamflow index were chosen. Both observed and forecasted streamflow showed no drought evidence in this basin, but the period of study was particularly short for drought analysis.

SSI: Standardized Streamflow Index

Vicente-Serrano et al. (2012) provided the first study on the analysis of streamflow droughts using the standardized streamflow index (SSI). The use of the SSI index allows accurate spatial and temporal comparison of the hydrological conditions of a stream or set of streams. Several three-parameter distributions (lognormal, Pearson Type III, log-logistic, general extreme value, generalized Pareto, and Weibull) and two different approaches to select the most suitable distribution were tested by using a monthly streamflow data set for the Ebro Basin (Spain). No single probability distribution was suitable for obtaining a robust standardized streamflow series. The BMF and MD approaches improved the results in the expected average, standard deviation, and the frequencies of extreme events of the SSI series. The obtention of the SSI required using different distributions for each gauging station and month of the year. Both approaches are easy to apply and provide similar results in the quality of the hydrological drought indexes, while proving flexible to analyze contrasting hydrological regimes.

Vegetation drought indices

Previous sections dedicated to the SPI and SPEI indices already introduced the great interest of the forest community on the use of drought indices. In this section though, we focus on indices specifically designed to determine vegetation status under drought conditions.

DRI: Drought response index

Bidinger et al. (1987a,b) developed a drought response index (DRI) to identify genotypes that are tolerant or susceptible to drought. Thus, it is a drought index focused on the plant response according to their physiology.

In the Iberian Peninsula, this index has been used in forest research first by Bogino et al., (2009), who explored the associations between tree-ring width and climatic variables to see drought index impact and tree age on radial growth of Scots pine (Pinus sylvestris L.). Six tree-ring width chronologies for P. sylvestris were used to obtain the association between tree growth and climate. The drought response index (DRI) was used to detect the effects of aridity. Tree-ring width was positively correlated with rainfall in the growing season. The response to climatic variables depended on the age of the trees: more of the variability was explained by climatic variables in young stands than in old stands.

Site and Age Condition the Growth Responses to Climate and Drought of Relict Pinus nigra Navarro-Cerrillo et al. (2014) expanded the use of the DRI to assess how tree age modulates the main climatic drivers of radial growth in Pinus nigra subsp. Salzmannii. Tree-ring width chronologies for two age groups of the trees were built to evaluate their responses to climate by relating them to monthly precipitation and temperature with the drought index (DRI). We found that drought is the main driver of growth. Previous autumn and the spring of the year conditions affect tree-ring formation more in xeric than in mesic sites, which is similar to other results of same and similar species using the DRI or other vegetation-related indices.

NDVI: Normalized Difference Vegetation Index

The NDVI is the most popular index used in the monitoring of vegetation conditions. The Index consists of the ratio of infrared spectrum light absorbed and visible red reflected light by vegetation. Plants absorb solar radiation in the NIR band to generate photosynthesis. But in that process, leaves re-emit some visible near-infrared spectral region. The greener (healthy) a plant is, the higher the ratio between NIR and Red, while the negative values of the ratio determine plants under restrictions to photosynthesize or less plant cover of the soil. With the increasing availability of visible and infrared remote sensing products, this index has become widespread due to its simplicity and representativity.

Vicente-Serrano et al., (2013) evaluated the response of the Earth land biomes to drought by correlating the SPEI with the NDVI, tree-ring growth series, and Aboveground Net Primary Production (ANPP) as global indicators of vegetation activity. Results suggested arid and humid biomes are both affected by drought. We found that arid biomes respond to drought at short time-scales; that is, there is a rapid vegetation reaction as soon as water deficits below normal conditions occur. Humid biomes also respond to drought at short time-scales, but in this case, plants have a poorer adaptability to water shortage. On the contrary, semiarid and subhumid biomes respond to drought at long time-scales, probably because plants are able to withstand water deficits, but they lack the rapid response of arid biomes to drought. Authors outline the importance of understanding the time-scales at which drought influences vegetation.

Gouveia et al. (2017) further explored the SPEI-NDVI relationship to analyze drought impacts on vegetation over the entire Mediterranean basin. Remote sensing data fed the NDVI and climatic databases the SPEI series used to find correlations on drought response of vegetation at different time scales (1–24 months) and seasons. Results show the frequent vast affection of drought to the Mediterranean vegetation. The higher control of drought on vegetation occurs in February and May, mainly over the drier vegetation communities (Mediterranean Dry and Desertic) at shorter time scales (3 to 9 months). Temperate Oceanic and Continental vegetation types experience drought control at longer time scales (18–24). The strong control of drought on vegetation observed for Mediterranean dry and desert vegetation types located over areas with high negative values of water balance emphasizes the need for an early warning drought system covering the entire Mediterranean basin.

Vicente-Serrano et al. (2018) further explored the potential of the NDVI in combination with the SPEI to characterize drought impact on vegetation in Spain. A high-resolution spatial database of the NDVI was used to assess the time scales of the sensitivity of vegetation to drought from 1981 to 2015. Results showed vegetation activity is largely controlled by the interannual variability of drought. More than 90 % of the land areas exhibited statistically significant positive correlations between the NDVI and the SPEI during dry summers (JJA). Results also indicate that vegetation types located in arid regions showed the strongest response to drought, which is consistent with the previous study of Gouveia et al. (2017).

Páscoa et al. (2018) further investigated the impacts of drought events on vegetation activity in the period 1998–2014 in southeastern Europe using the SPEI and the NDVI obtained from SPOT/VEGETATION. Authors generated a correlation analysis between monthly NDVI and SPEI to identify the simultaneous occurrence of drought events and low vegetation. Results showed the area with positive correlation between the two indices peaked in summer (July) on agricultural land, with drought impacts spanning from May to October. Forests seem to be less sensitive to drought, but equally affected the most in summer. High altitudes showed a positive effect of dryness on the vegetation activity in June, which was never before reported.

Gazol et al. (2018) incorporated the use of the tree ring width index (TRWi) with the NDVI as proxies of forest productivity for 11 tree species and 502 forests in Spain corresponding to Mediterranean, temperate, and continental biomes. Four different components of forest resilience to drought were obtained based on TRWi and NDVI data before, during, and after four major droughts (1986, 1994–1995, 1999, and 2005). The analysis evidenced the better sensitivity of the TRWi compared to the NDVI data to drought resilience. Resilience seems related to both drought severity and forest composition. Evergreen gymnosperms dominating semi-arid Mediterranean forests showed the lowest resistance to drought, but higher recovery than deciduous angiosperms dominating humid temperate forests. Semi-arid gymnosperm forests presented a negative temporal trend in the resistance to drought, with faster recovery, but this pattern was absent in continental and temperate forests. Authors outlined angiosperms and gymnosperms of temperate and continental sites are the most exposed to recurring droughts due to less chance of recovery. Soon afterwards, Gazol et al., (2020) expanded the evaluation of impacts of drought on forest growth with focus on legacies. Legacy effects of drought were calculated as the differences between detrended-only TRWI and NDVI series. Superposed Epoch Analysis (SEA) was used to estimate whether legacy effects differed from random or were related to water balance, growth and type of species. Legacy effects were identified in the NDVI series, especially in the following year, but not for more than 10% of the series. Gymnosperms showed larger first-year drought legacies than angiosperms. The study highlights the importance of evaluating legacies on drought response of forests, since scenarios indicating increasing droughts may challenge the survival of Iberian forests.

Sánchez et al. (2018) also used the NDVI but from an agricultural approach using the NDVI in combination with the SMADI soil moisture drought index. While the focus of the study was on the evaluation of the SMADI index, the NDVI proved of great consistency in comparison to this soil moisture index for the assessment of agricultural droughts.

VTCI: Vegetation Temperature Condition Index

An additional drought index focused on vegetation is the Vegetation Temperature Condition Index (VTCI), which is a drought index developed as a combination of the land surface temperature (LST) and the NDVI. This index was applied by Mühlbauer, Costa and Caetan, (2015) in a study aimed to identify local droughts during spring and summer seasons in relation to the NAO anomalies. To calculate the VCTI, authors derived biweekly information on LST and NDVI from MODIS/Terra and produced VTCI–NAO correlation maps. Results reflected a typical Mediterranean pattern in most parts of Iberia with spring seasons marked by great variability of precipitation and summers defined by dry weather, particularly in the south. NAO exerts its greatest influence in April and June, months that are particularly important for plant growth. The index also allowed evaluating agricultural lands, which revelaled to be less resilient to drought.

VCI and TCI: Vegetation Condition Index and Temperature Condition Index

The Vegetation Condition Index was developed by Kogan (1995) to identify drought events and their onset focusing on their impact on vegetation, in particular the thermal reflectance of vegetation as indicator of their health status when affected by drought. The Temperature condition index (TCI) (also developed by Kogan,1995) is used to determine stress on vegetation caused by temperatures and excessive wetness. Conditions are estimated relative to the maximum and minimum temperatures and modified to reflect different vegetation responses to temperature.

In the Iberian Peninsula, Ribeiro et al. (2019) has recently applied these indices in combination with the SPEI to evaluate the agricultural drought risks of rainfed crops in Iberia. The authors used the copula theory to estimate joint probability distributions describing the amount of dependence between drought conditions and crop yield anomalies of two major rainfed cereals in the Iberian Peninsula (wheat and barley), in the period 1986–2016. The results suggest that, in general, the joint behavior of yield anomalies and drought conditions exhibits a dependence between the extreme values, whereas barley exhibits greater probabilities of joint extreme low values of yield and drought indicators. Moreover, while TCI is mainly used in copula models indicating greater probabilities of joint extreme high values of wheat and drought indicators (Gumbel models), VCI and SPEI are mainly associated with copula models indicating greater probabilities of joint extreme low values (Clayton models). The estimated conditional probabilities of occurrence of crop-loss are illustrated at the province level and suggest that agricultural drought risk increases with drought severity in most of the provinces. In conclusion, barley exhibits greater agricultural drought risk in comparison to wheat.

VHI: Vegetation Health Index

The VHI was developed by Kogan (1990) as one the first attempts to monitor and identify drought-related agricultural impacts using remotely sensed visible, infrared and near-infrared channels from the AVHRR mission to identify and classify stress to vegetation due to drought. This index takes into account ecosystem features in terms of fluctuations between prescribed maxima and minima of NDVI (via VCI) and of Land Surface Temperature (LST; via the Thermal Condition Index, TCI), and is estimated as the sum of these two contributions.

Bento et al. (2018) used the Vegetation Health Index (VHI), which is calculated as the sum of the two weighted terms dependent on NDVI and LST to characterize the two contribution of vegetation stress and temperature to drought in combination with the SPEI for the period 1982-2009. The assumed weight is 0.5 since we don't know the specific contribution of each term. The VCI, TCI and VHI for the period of study of the series is then correlated with the multiscalar drought indicator SPEI. Results of the correlations between VCI-SPEI and TCI-SPEI show that the relative contributions of VCI and TCI to vegetation health depend on vegetation cover: the effect of drought is more evident in the case of VCI in semiarid climate classes where the limiting factor is water; while the effect of drought is more obvious in TCI for wetter climate classes where the limiting factor is solar radiation. This leads to the conclusion that by maximizing the correlations between VHI and SPEI, over a climatological period, it is possible to evaluate the relative roles of VCI and TCI to VHI for different climate regions.

NDDI and NDWI: Normalized Difference Drought and Normalized Difference Water Index

The Normalized Difference Water Index developed by Gao, (1996) is a satellite-derived index similar to the NDVI but using another spectral window, the one from the Near-Infrared (NIR) and Short Wave Infrared (SWIR) channels taking advantage that the SWIR reflectance reflects changes in leaf water content and the mesophyll structure. SWIR reflectance is negatively related to leaf water content. The NIR reflectance is affected by leaf internal structure and leaf dry matter content. The NDDI is the Normalized Difference Drought Index developed by Renzo et al., (2010) in an article whose purpose was to analyze drought merging traditional indexes, such as NDVI and NDWI, of easy estimation with Landsat data for the period 2001-2009. The NDDI provided an appropriate measure of the dryness of a particular area, because it combines information on both vegetation status and water content of the vegetation. Thus, the NDDI has a stronger response to summer drought conditions than NDVI or NDWI alone, and it therefore improves the identification of drought in sensitive vegetation.

Gouveia et al. (2012) used the NDWI to assess how the water availability in the canopy affects the occurrence of forest fires and forest-fire recovery in Portugal during the drought of 2004/2005 that end up in forest fires burning large areas of Iberia. Authors estimated vegetation recovery using the mono-parametric model, which relies on monthly values of the NDVI from 1999 to 2009, at 1 km resolution, as obtained from the VEGETATION-SPOT5 instrument. Besides the standard NDVI, the NDWI and the NDDI were computed in order to evaluate drought intensity. The extreme water stress conditions during drought events delayed the regeneration process. Regarding burnt areas, fires are more violent when vegetation is more stressed and dryer in summer after high vegetation density and high moisture content during the months before the fire. Results show also that, in general, shrubs hold less quantity of very dry biomass, while needle leaf presents higher amounts of it.

Composite / Modelled drought indices

Palmer drought indexes

The Palmer Drought Indices (Palmer , 1965) have historically been the most commonly referenced measures of drought in the United States (Anderson et al., 2007). The indices are calculated with time series measurements of daily precipitation and air temperature, running a simple two-layer soil model to estimate ET, soil moisture storage, recharge, and surface runoff. Three are the primary indices of Palmer, each with a characteristic timescale. The Palmer moisture anomaly index (Z index) represents the departure of modeled soil moisture from the climatic mean for each month, independent of antecedent conditions. Longer-term drought indices are then developed from the Z index. The Palmer drought severity index (PDSI; a measure of meteorological drought) and the Palmer hydrological drought severity index (PHDSI) result from an analysis of a monthly Z index time series with increasing thresholds for determining when drought conditions have been alleviated. The PDSI relates drought severity to the accumulated weighted differences between actual precipitation and the precipitation requirement of evapotranspiration (ET). Although commonly referred to as a drought index, the PDSI is actually used to evaluate prolonged periods of abnormally wet or abnormally dry weather. The PHDSI is the hydrologic version of the PDSI.

The algorithms used to compute the index values are complex and opaque, and drought severity thresholds are somewhat arbitrary. The core model neglects the effect of seasonal changes in vegetation cover, snowmelt, and frozen soil on water budget partitioning (Alley, 1984). Index values are not strictly comparable between seasons and climatic regions across the United States, complicating interpretation of the PDSI at the continental scale (Alley , 1984; Guttman , 1997). The indices are also highly sensitive to choice of calibration coefficients and soil available water capacity (Karl, 1986).

There are not many examples of Palmer drought indices used in the Iberian Peninsula and they have been mainly applied to forest or agricultural research due to the nature of the Palmer family of indexes. Sánchez-Salguero et al. (2012) used a version of the PDSI, the self-calibrated PDSI (SCPDSI) to evaluate the negative impacts of severe drought on the growth and vigor of four pine species (Pinus sylvestris, Pinus nigra, Pinus pinaster, Pinus halepensis). Authors used dendrochronological, defoliation, basal area increment and dynamic factor analysis to quantify the responses of trees to droughts identified with the DRI and the scPDSI index. Results indicated defoliation levels and basal area increment were higher in those species more vulnerable to drought-induced xylem embolism (P. sylvestris) than in those more resistant (P. halepensis).

Jan Esper et al. (2015) also adopted the PDSI to investigate the synoptic systems influencing drought impact on Juniperus thurifera from the information contained in tree rings, especially of spring and summer drought conditions. Results reveal that the northwestern sampling site is predominantly controlled by Atlantic weather, while the southeastern site mainly reflects Mediterranean climate patterns. Tree ring growth allowed the reconstruction of May-June PDSI variability back to the early eighteenth century, indicating severe drought (PDSI < -9) in southeastern Spain in 1782, 1828, 1869, 1981, and 2005. The new PDSI record coheres well with other historical and dendrochronological series.

The article of Vicente-Serrano et al. (2017) evaluating seven drought indices to quantify drought severity and identify possible changes in the frequency and duration of droughts also included the use of Palmer indices. The dataset included seven drought indices for the period 1961–2014 with km spatial resolution. The self-calibrated Palmer Drought Severity Index (scPDSI), the standardized Palmer Drought Severity index (sPDSI), the Palmer Hydrological Drought Index (PHDI), the modified Palmer Drought Severity Index (WPLM), and the Palmer Z index were included in the published dataset together with the SPI and the SPEI.

Peña-Gallardo et al. (2017) used the family of Palmer indices with an agricultural scope aiming to evaluate crop failure due to drought. The self-calibrated Palmer Moisture Anomaly Index (Z-Index), the self-calibrated Crop Moisture Index (CMI) and the Standardized Palmer Drought Index (SPDI) were calculated together with the SPI and SPEI at different time scales in order to identify the dry events occurred in Spain and determine the duration and intensity of each event. The identified drought episodes were correlated with crop production estimated and final crop production data provided by the Spanish Crop Insurance System for the available period from 1995 to 2014 at the municipal spatial scale, with the purpose of knowing if the characteristics of the drought episodes are reflected on the agricultural losses, of wheat and barley in particular. The results indicate the existence of an agreement between the most important drought events in Spain and the response of the crop productions and the proportion of hectare insurance. Results indicate a higher competence of the drought indices calculated at different time scales (SPEI, SPI and SPDI) when the beginning and end of the drought events correspond with the critical periods of crop failure.

Peña-Gallardo et al., (2019) further explored the comparison of multiple drought indices to evaluate agricultural yields of the rain-fed crops in Spain. The indexes compared were the SPI and SPEI with the Palmer family of indices PDSI, PZ, Z, PHDI, PMDI and SPDI. She compared two crop yield datasets at different spatial scales. Results showed that the SPI and SPEI indices (the multi-scalar indices) correlated well with crop yields but suggest that the characteristics of the region, period of the year and drought timescale may cause the differences in yield patterns. The PHDI, PDSI and PMDI showed the weakest relationship to crop yields, and the best uni-scalar index was the Z index. Barley shows lower sensitiveness to water availability at multiple vegetative stages. Both crops respond quickly to anomalies, especially to those of temperature and during spring. Northern plateau was the most sensitive area to drought.

Combined Drought Index (European drought observatory):

The CDI, which was developed by Sepulcre-Canto et al. (2012), is derived by combining three drought indicators produced operationally in the EDO framework - namely the Standardized Precipitation Index (SPI), the Soil Moisture Anomaly (SMA), and the FAPAR Anomaly - in such a way that areas are classified according to three primary drought classes: (1) “Watch”, indicating that precipitation is less than normal; (2) “Warning”, indicating that soil moisture is in deficit; and (3) “Alert”, indicating that vegetation shows signs of stress. Two additional classes - namely “Partial recovery” and “Recovery” - identify the vegetation recovery process.

Jiménez-Donaire, Tarquis and Giráldez, (2020) is the only case applying the CDI in the Iberian Peninsula so far. Authors built the CDI applying the bucket type soil moisture model and the NDVI data monitoring vegetation datasets together with the SPI evaluating rainfall deviations. The CDI analysis was applied over the period 2003–2013 to five study sites, representative of the main grain-growing areas of SW Spain. The performance of the CDI levels was assessed by comparison with observed crop damage data. Results indicated a good match between crop damage and the CDI. Important crop drought events in 2004–2005 and 2011–2012, distinguished by crop damage in between 70 % and 95 % of the total insured area, were correctly predicted by the proposed CDI in all five areas.

Socioeconomic indices

The last of the categories of drought index identified in the Iberian bibliography is the socioeconomic ones devoted to investigate the impacts of drought in the hydrologic system. These indices tend to focus on the socioeconomic aspects of drought in the water management protocols.

SI (Ie): State Index

Haro-Monteagudo et al., (2014) addressed the evaluation of drought plans in the water management systems which use a System Indicator (I_e) of drought based on current and past data. The index is defined based on the water resources of the basin depending on their specific contribution and defines four levels of status of the system: Normality, Pre-alert, Alert and emergency. Authors indicate this approach may overlook multiple risks associated with drought and suggest the use of decision support systems to analyze the uncertainty and risk of failure of the system under drought stress. The method proposed aims to anticipate the future probable status of the system, define the current drought scenario and optimize the decisions to mitigate measures and minimize the probability of overreaction during a drought situation.

Last authors Haro-Monteagudo et al. (2017) further developed the methodology to support and complement drought monitoring and early warning in regulated water resources systems. It is based on the combined use of two models, a water resources optimization model and a stochastic streamflow generation model, to generate a series of results that allow evaluating the future state of the system. Results for the period 1998–2009 in the Jucar River Basin show that accounting for scenario change risk can be beneficial for basin managers by providing them with information on the current and future drought situation at any given moment. The article highlights the advantage of the method assessing future scenarios compared to the traditional State Index (SI) approach applied by the River Basin Agencies in Spain.

5.6.2 WEI: Water Exploitation Index

Vargas and Paneque, (2019) proposed the use of a different socioeconomic index to complete the evaluation of drought risks: the Water Exploitation Index (WEI). Authors aim to test if the unsatisfactory integration of drought-risk and water resources management strategies increases the vulnerability to drought. Several aspects are taken into consideration: (i) the integration of the predictable effects of climate change; (ii) the pressure on water resources that determines the sensitivity of the systems; and (iii) the development and implementation of drought management plans. In the second of the aspects, sensitivity, the state of pressure on water resources was analyzed, and is characterized with the Water Exploitation Index (WEI). The results showed worrying WEI levels in certain basins which may suffer increased drought-risk vulnerability under unfavorable scenarios. Authors highlight the high vulnerability of most of Spain despite important advances in the protocols to manage drought.

HDII: Hydrological Drought Index Insurance

The hydrological drought index insurance (HDII) proposed by Maestro, Bielza and Garrido, (2016) is an interesting example of a socioeconomic index with agricultural scope. The aim of the authors was to propose an insurance tool to help irrigators manage the risk of water scarcity in the framework of the Spanish Crop Insurance System (SCIS). Only the United States Insurance System provides this type of coverage, but has very restrictive conditions. The hydrological drought index insurance (HDII) is a tool to determine the levels of compensation to the water deficits suffered in irrigation districts. HDII estimates the level of farmer losses due to water shortages. The unitary indemnity is given per square meter based on the level of guarantee of the water allotment and the deficit caused by droughts. HDII is applied to the Bardenas Irrigation District V (ID-V) in Ebro Basin, and authors analyzed the hedging effectiveness of the instrument comparing ID-V's gross margins with and without the insurance contract. Results suggest that insurance schemes could provide an effective mean of reducing farmers' vulnerability to water shortages, by including them as a new line in the SCIS, while ensuring the optimization of resources in drought management.

Land-Surface Models and drought

LSMs: Land surface models

Modelling is an interesting tool to evaluate drought related processes because it allows comparing the effects of specific factors of interest in the process while enabling generating long-term simulations of the entire system into the past or the future scenarios (Van Loon et al., 2012). Among the multiple types of models, physical models are particularly interesting to assess the interactions between processes, because they aim to reproduce processes as a system of fluxes, exchanges and storages, which is particularly advantageous to investigate complex processes such as those involved in drought analysis (Vidal et al., 2010b). This is the case of Land-surface models (LSMs) which explicitly simulate the water and energy exchanges at the interface of the land-atmosphere system, including vegetation interactions (Barella et al., 2019). Given that observations such as precipitation and streamflow are abundant but other variables of difficult observation, such as soil moisture, are scarce, LSMs provide the possibility to physically simulate those less explored water cycle processes affecting drought.

When LSMs run uncoupled from atmospheric models they can be handled as a physically distributed hydrological model able to simulate water balances and runoff such as with the LSM based SAFRAN-ISBA-MODCOU (SIM) model chain (Habets et al., 2008) or the ORCHIDEE model (De Rosnay and Polcher, 1998; Krinner et al., 2005). The possibility of analyzing most processes of the system comes with the toll of the complexity of LSMs, which limits their use as hydrological models for daily basin management, where numerical and statistical hydrological models offer better results in terms of streamflow simulation but do not provide understanding of the processes beneath (Barella et al., 2019).

Additional disadvantages of LSMs can appear when simulating soil moisture, vegetation activity or other complex processes, due to the uncertainties in the forcing data (Koster et al. 2009), parametrization (Nearing et al. 2016) or resolution. Consequently, uncertainties of LSMs derived from input data are still relevant (Yilmaz and Crow 2013; Wang et al. 2009; Fan et al. 2011; Tallaksen and Stahl 2014) and, thus, the use of ensembles is recommended (Mo and Lettenmaier, 2014). Referred to soil moisture evaluation but valid for many other processes, the assimilation of data in LSMs is an approach with great potential to reduce uncertainty (López et al., 2016), but is often challenging (Escorihuela and Quintana-Seguí 2016).

LSMs also play an important role in monitoring and prediction systems due to their capability to analyze variables that are difficult to observe either from in-situ or remote observation, such as root zone soil moisture (Barella et al., 2019). The insights LSMs provide about the mechanisms of multiple processes are especially relevant and useful to the improvement of decision making (Sheffield and Wood 2007, 2014).

LSMs for drought monitoring

SURFEX

SURFEX (Masson et al., 2013) is a land and ocean surface model able to describe the surface fluxes and the evolution of four types of surfaces: nature, town, inland water and ocean. SURFEX can be run in offline mode or in coupled mode (from mesoscale models to numerical weather prediction and climate models). In addition to momentum, heat and water fluxes, SURFEX is able to simulate fluxes of carbon dioxide, chemical species, continental aerosols, sea salt and snow particles. In Spain, SURFEX is the basis of the SASER (SAFRAN-SURFEX-Eaudyssée-RAPID) modelling chain, similar in spirit to the previously mentioned SIM. Soil and vegetation parameters in SURFEX are derived from the ECOCLIMAP database (Masson et al., 2003). SURFEX lacks a routing scheme for runoff, which is the reason why SASER uses the RAPID routing model (David et al. 2011) via Eau-dysee (Habets et al., 2009). An important limitation of SASER is that it does not represent groundwater processes. Since SAFRAN (*Système d'analyse fournissant des renseignements atmosphériques à la neige*) is the meteorological mesoscale system associated to SURFEX, first a SAFRAN validation is required.

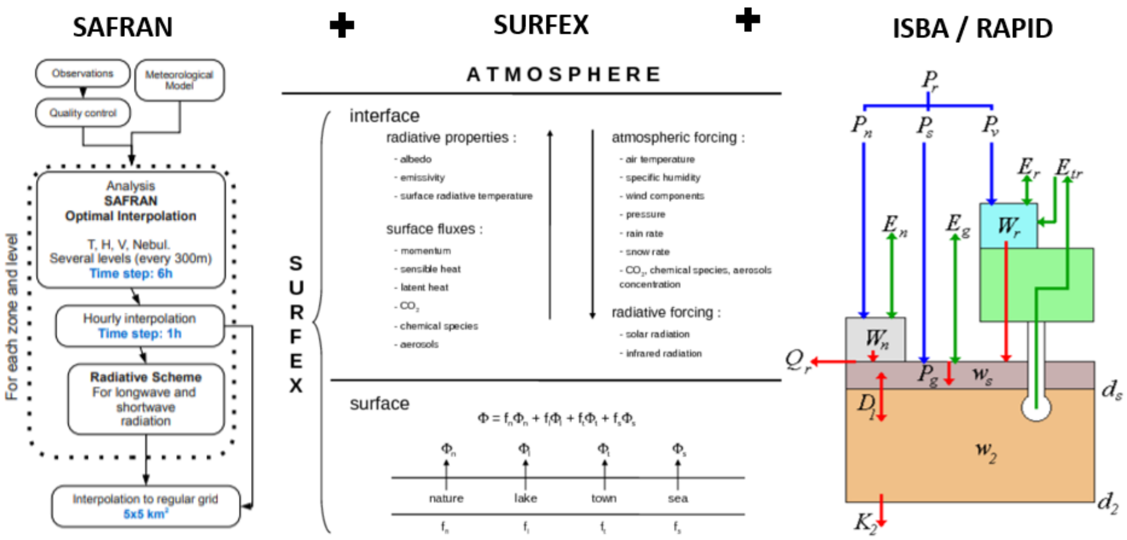


Fig. 4: Simplified modelling scheme of SASER modeling chain (SAFRAN+SURFEX-ISBA+RAPID).

The validation of SAFRAN in the Iberian Peninsula came after its validation in France Quintana-Seguí et al. (2008) and Vidal et al. (2010a). Validation comprised testing air temperature, humidity, wind speed, rainfall, and incoming radiation data from observations of Météo-France's network. Temperature and relative humidity were well reproduced, presenting no bias. Wind speed tends to have some bias. The precipitation analysis was robust and not biased, mainly due to the spatial heterogeneity of the precipitation within the geographical zones of analysis. Analysis of incoming solar radiation showed biases, especially in the coast.

Quintana-Seguí et al. (2016) addressed the validation of SAFRAN in Spain. To support the validation, SAFRAN was also compared to the SPAN analysis system and the meteorological model HIRLAM-HNR, both operational at AEMET. This was the first study that shows an application of SAFRAN outside of France. Using one year of observational data, the results showed that both SAFRAN and SPAN had a similar performance, which was also similar to SAFRAN's performance in France. Thus, SAFRAN and SPAN are both good tools to force land surface models at high resolution under the assumption of climatically homogeneous zones. Author tested two zoning schemes, one based on the AEMET meteorological warning zones and another one based on hydrological catchments. Results were better using meteorological warning zones but with very small differences with the hydrological one. Some limitations were observed: wind speed is underestimated, as it was identified in France, and both SAFRAN and SPAN worked better in flat areas than rugged ones. This can be problematic in Iberia where most of the water resources originate in mountainous regions.

Escorihuela and Quintana-Seguí, (2016) applied SURFEX to compare the performance of different global remote sensing soil moisture products (ASCAT, AMSR and SMOS) over a region representative of several Mediterranean landscapes located in the Northeast of the Iberian Peninsula with a focus on the regional or local scale required for agricultural and water management. The area displays varied topography along with the major land cover classes of the Mediterranean: dryland and irrigated crops, forests and natural vegetation (grass-shrubs). Results seemed very dependent on the two normalizations used to make the data comparable. Using no smoothing window, ASCAT is the soil moisture product that correlates best with the LSM over all cover classes. Using a smoothing window, AMSR-E tends to outperform other soil moisture products. One of the normalization methods is not able to identify irrigation due to its sensitivity to precipitation. The comparison shows in general good agreement for all soil moisture products with the LSM over flat, non-irrigated areas which are not close to the sea. SMOS has difficulties in areas close to the sea and in areas with steep relief and the current version of the L2 is challenged in forested areas. ASCAT shows some limitations over agricultural and natural vegetation where it shows an increase of soil moisture from June to October probably due to increase of penetration depth in dry soil moisture conditions. AMSR-E shows a clear vegetation cycle over all the land cover classes. From all the remote sensing products, SMOS is the only one able to see irrigation and the only that does not show clear vegetation or roughness effects.

Soon afterwards, SAFRAN was validated at the national scale (Quintana-Seguí et al., 2017). The study compared the performance of SAFRAN with the one of Spain02 (Herrera et al., 2012) and the ERA-INTERIM (Berrisford et al., 2009) database as representative of global low-resolution products together with AEMET observations. SAFRAN seems a robust product of performance very close to that of Spain02 and much better than ERA-Interim. ERA-Interim has, though, some advantage on reproducing spells compared to the high-res SAFRAN and Spain02.

Both SAFRAN and Spain02 underestimate high precipitation events, especially SAFRAN. The overestimation of low precipitation events and the underestimation of intense episodes may have consequences on hydrological modelling as well as on drought monitoring.

Quintana-Seguí et al., (2017) initiated the evaluation of the LSM SURFEX for drought monitoring, task for which, in the framework of the project HUMID (Hydrological understanding and modelling of Iberian Drought), also remote sensing-based products are analyzed. The project focused on drought propagation from precipitation to soil moisture and stream flow, while also addressing the analysis of the convenience of RCMs in comparison to ERA-Interim to monitor drought. The project also aimed at improving the hydrological side of the SASER chain. The project incorporated the application of multiple remote sensing data, downscaled from SMOS and SMAP to gain insight on soil moisture processes. The project has also explored if both LSMs and remote sensing improve the quantification of irrigation. In conclusion, the project pursues the understanding and monitoring of drought in a Mediterranean and semi-arid context in the context of droughts.

One of the studies developed in the project HUMID was the Barella et al. (2019) study comparing two land-surface models and three forcing datasets at different resolutions to evaluate their usefulness in providing information about drought and its mechanisms (via the analysis of diverse variables such as precipitation, soil moisture and streamflow). The study aimed to evaluate drought in Spain using the high-resolution SAFRAN data (meteorologic drought) the ORCHIDEE (soil moisture drought) (De Rosnay and Polcher, 1998, explained in detail in the following section) and SIMPA (hydrological drought) (Monreal and Ripoll, 1996) as reference to compare the influence of using difference RCMs such as CNRM-RCSM4, COSMO-CLM and PROMES. Meteorological (SPI), soil moisture (SSMI) and streamflow (SSI) drought indexes were used for the comparison of the performance of the RCMs. Authors additionally evaluated the uncertainties derived from the forcing datasets and model structures of LSMs. Results show that RCMs improve meteorological drought representation. Uncertainties are identified in their characterization of soil moisture and hydrological drought due to the model structure, which affects the temporal scale at which precipitation propagates to soil moisture and streamflow. None of the RCMs analyzed can be clearly identified as showing the best performance with respect to hydrological drought representation. Some RCMs provide propagation to soil moisture too quickly, while others show richer spatial patterns, depending on the region of Iberia. In any case, RCMs provide added value to meteorological drought representation, but with relevant uncertainties in soil moisture and hydrological drought representation depending on model physics. RCMs design also influenced propagation and should be applied with care over soil moisture and hydrological drought analysis.

Khodayar, Coll and Lopez-Baeza, (2019) evaluated the synergy of multi-resolution soil moisture satellite estimates from SMOS over a dense network of ground-based SM measurements with SURFEX-ISBA to examine the benefits of the SMOS level 4 on high-resolution estimation of soil moisture. Authors also compared SMOS-L3 (~25 km) and SMOS-L2 (~15 km) to SMOS-L4. SURFEX_ISBA model is used in combination with high-quality atmospheric information data, from the ECMWF and SAFRAN to obtain representative mapping of SM. Results demonstrate all SMOS products correctly capture the temporal patterns, but the spatial patterns are not accurately reproduced by the coarser resolutions, in contrast with the point-scale variability tendency of in situ measurements. The temporal resolution of the period of the SMOS satellite compromises the averaged SM representation for longer periods than a day. Results show better estimates during autumn-winter than during spring (vegetation activity) and summer (very los SM in Iberia). In any case, SURFEX_ISBA fed by SAFRAN proved able to produce regional SM maps with high accuracy particularly for crop monitoring and crop development strategies in a context of drought analysis.

Quintana-Seguí et al. (2020) uses SURFEX-ISBA and LEAF-HYDRO to simulate drought propagation from precipitation to soil moisture and streamflow for the period 1980-2014 forced by the Spanish SAFRAN and the global eartH2Observe datasets. We produce standardized indices for precipitation (SPI), soil moisture (SSMI) and streamflow (SSI). Results show that the model structure causes important uncertainties in the LSM-based hydrological simulations. Propagation scales for drought regarding both soil moisture and streamflow are overly dependent on the model structure. Authors outline that uncertainty from the forcing datasets have an impact on the results generally of less impact than model formulation.

Other authors used the capabilities of SURFEX focus on a different field, like the one of surface temperatures in relation to vegetation activity (Miguel Nogueira et al., 2020). This study aimed to evaluate the representation of land surface temperature (LST) and vegetation coverage over

Iberia using the LSM CHTESSEL (Carbon-Hydrology Tiled ECMWF Scheme for Surface Exchanges over Land) and SURFEX-ISBA for the 2004–2015 period. The results showed that the daily maximum LST simulated by CHTESSEL over Iberia was cold-biased during summer months compared to remote sensing data, apparently due to misrepresentations of the vegetation cover. Conversely, SURFEX simulations did not display cold bias thanks partly to the better representation of vegetation cover defined by ECOCLIMAP in SURFEX and partly due to the capability to model interactive vegetation. The work outlines the advantage of LST, a key variable in surface–atmosphere energy and water exchanges, to improve the model's representation of land surface processes, the uncertainties of CHTESSEL in the production of unbiased estimates and the importance to consider the interaction between vegetation land–atmosphere exchanges in representing land surface, on which SURFEX has some advantage.

Dari et al. (2021) followed the approach of Escorihuela and Quintana-Seguí (2016) to compare remote sensing with LSM estimates of soil moisture over large irrigation areas developing a method to distinguish irrigated areas depending on the crops' signal on SM. The study used the SMOS 1 km and SMAP datasets at 1 km and 9 km, Sentinel-1 at 1 km, and ASCAT at 12.5 km. The 1 km resolution versions of SMOS and SMAP were downscaled with the algorithm DISPATCH (Merlin et al., 2012). SURFEX-ISBA LSM provides the modelling SM data at 1km. Results indicate SMOS, and especially SMAP, identify irrigation the best. Maps of irrigated areas derived from SMAP agree well to the ground truth and can be distinguished from rainfed crops using a K-means method of clustering.

Stefan et al., (2021) adopted the use of SURFEX to compare estimates of the root-zone soil moisture (RZSM) obtained from high-resolution remote sensing products. The study tests the possibility to estimate RZSM from SSM estimates such as SMAP. Authors propose to test a method using a time constant τ calibrated per land cover type, to be used as input of the recursive exponential filter that derives RZSM estimates from 1 km SMAP SSM. The estimates are then validated with scaled in situ observations at different depths, over two different areas: rainfed and irrigated crops. In general, the estimates agree well with the observations over the rainfed crops, especially at a 10 cm and 25 cm depth. Correlation coefficients for these depths are high down to 25 cm. Results are poorer at irrigated areas apparently due to heterogeneity. For the rainfed site, it was found, as expected, with increasing τ, increasing NS and correlations with the deeper layers, suggesting a better coupling. Nevertheless, a strong correlation with the surface (5 cm) or shallower depths (10 cm) observed over certain sites indicates a certain lack of skill of the filter to represent processes which occur at lower levels in the SM column. All in all, calibration accounting for the vegetation was shown to be an adequate methodology to tune the recursive exponential filter to derive the RZSM estimates. Effect of evapotranspiration in the profile is not well seen by the filter and may be explored.

Gaona et al. (2021) focus on the study of the propagation of drought processes using temporal correlations of standardized indices of precipitation, at several timescales, with one-month standardized indices of evapotranspiration and soil moisture. The timescale that maximizes the correlation is an estimation of the lags of drought propagation. Since observations of evapotranspiration and soil moisture are scarce, the LSM SURFEX-ISBA as well as some remote sensing downscaled products such as SMOS1km (Merlin et al., 2012) and MOD16 (Mu et al., 2013) can provide the estimates of these variables for the analysis of drought related processes. Results show important interactions between the anomalies of rainfall and evapotranspiration and a notable controlling capability of soil moisture on the modes of interaction with other variables: one with tendency to drought intensification under high-energy conditions and other with tendency to drought mitigation under low-energy anomalies.

ORCHIDEE

The ORCHIDEE (Organising Carbon and Hydrology In Dynamic EcosystEms) LSM (De Rosnay and Polcher, 1998) was developed by the "Institut Pierre-Simon Laplace" (IPSL). It can be run in a stand-alone mode or coupled to the GCM "Laboratoire de Météorologie Dynamique" (LMD-Z) (Li, 1999). This model adopts a diffusive equation with a multilayer scheme for the hydrological processes and a Fokker-Planck equation over the soil depth of 2 m distributed in eleven layers. The fine resolution is key to better model the interaction between the root profile and the soil moisture distribution at different depths, as well as infiltration processes. In addition, ORCHIDEE includes a sub-grid variability of soil moisture. For this, each grid box is divided into three soil moisture profiles 30 with different vegetation distribution, but the same soil texture and structure, obtained from the Zobler soil database (Post and Zobler, 2000).

The first application of ORCHIDEE in Iberia was conducted by Barella et al. (2017) who tested the capability of ORCHIDEE and the LSM model H-TESSEL to estimate soil moisture (surface soil moisture unless root zone moisture is indicated) in comparison with L-band remote sensing data such as that of the SMOS mission via temperature brightness (TB). The importance of brightness temperatures roots from its role in generating surface soil moisture estimates.

The two modelled sets of soil moisture were estimated using a radiative transfer model (CMEM) to calculate the brightness temperature based on state variables from ORCHIDEE and H-TESSEL. Measured and modelled brightness temperatures show a good agreement in their temporal evolution, but their spatial structures are not consistent. An empirical orthogonal function analysis of the brightness temperature's error identifies a dominant structure over the south-west of the Iberian Peninsula which evolves during the year and is maximum in autumn and winter. The analysis of spatial inconsistencies between modelled and measured TBs is important, as these can affect the estimations as well as result in misleading validations.

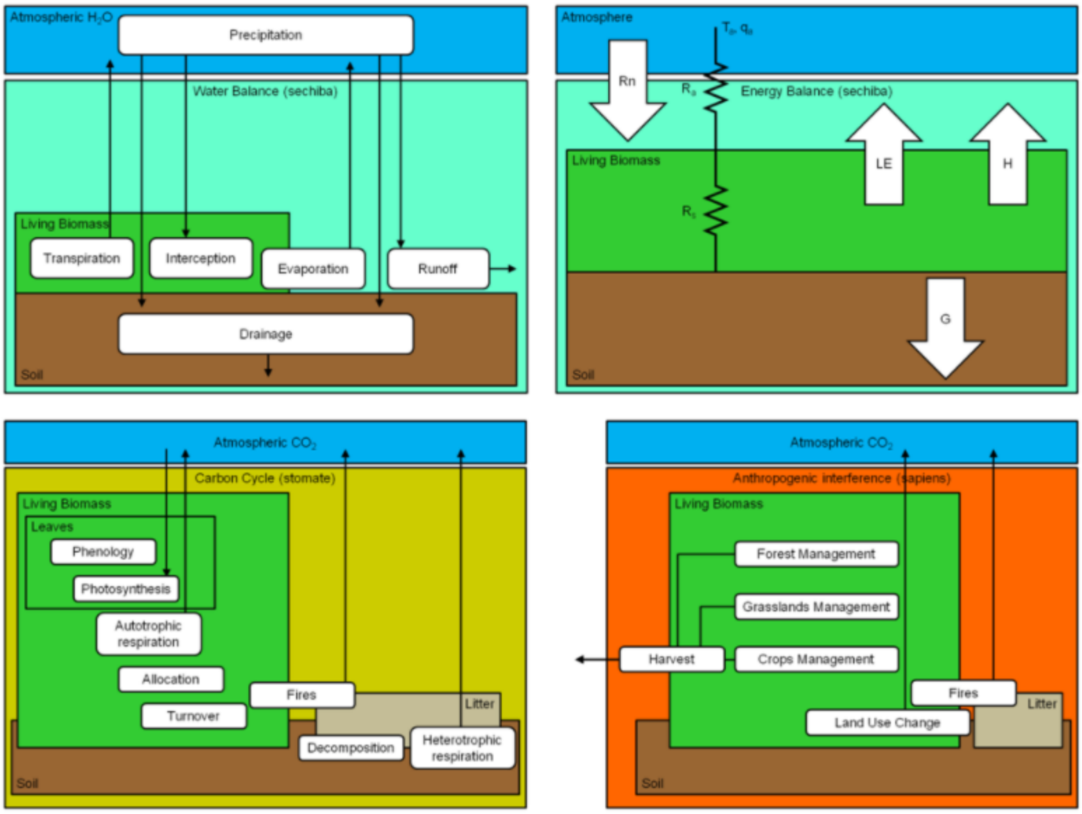


Fig. 5: Modelling scheme of ORCHIDEE for water balance (upper left), energy balance (upper right), biochemical processes (lower left) and anthropogenic causes (lower right).

Assimilation of river discharge in a land surface model to improve estimates of the continental water cycles

Developers of the ORCHIDEE model Wang et al. (2018) chose again the Iberian Peninsula to test the capabilities of this LSM, this time with a hydrological scope. Their work focused on streamflow which is a variable which may lack observations or be difficult to assess in the natural state. As a result, streamflow studies deal with large uncertainties. LSMs may help to estimate the components of the continental water cycles by merging the merits of observations and modeling approaches through data assimilation. The study used data assimilation techniques by merging the modeled river discharges of ORCHIDEE (natural state) LSM and the observations from the Global Runoff Data Centre (GRDC) to obtain optimized discharges over the entire basin. ORCHIDEE provides realistic natural state discharge estimations over the north of the Iberian Peninsula but overestimates discharge in the south and northeast regions where the blue water footprint is large. The disadvantage of addressing the problem of very altered basins with high blue footprint is the intense parametrization required to correct the bias. The E (P−E) of GLEAM (Global Land Evaporation Amsterdam Model, v3.1a) is lower (higher) than the modelled one, which could be due to the different P forcing and probably the missing processes in GLEAM. The study incorporates vertical and lateral water balance equations that embeds river routing on ORCHIDEE. An additional advantage of applying the LSMs to estimate discharges is that they can help to fill in gaps of the observation's series as well as provide data of ungauged basins. Authors outline also the interest of LSMs to estimate total contributions to seas, such as to the Mediterranean.

Barella et al. (2019) used an offline ORCHIDEE simulation forced with ERA to evaluate soil moisture and hydrological droughts. This study was already mentioned in the previous section. The purpose of the study was to compare RCMS estimates of meteorological, soil moisture and hydrological drought using SURFEX, OCHIDEE and SIMPA as reference. Results show that both the RCM definition and the LSM model structure influence the identification of the mechanisms of propagation of drought. Nonetheless, despite the limitations, the study shows RCMs have potential as alternatives for LSM simulations, while both approaches require improvements to solve the inconsistencies with data length, scales and feedback integration.

LEAFHYDRO

LEAF-Hydro is a development of the LSM LEAF (Land-Ecosystem-Atmosphere Feedback), the land model of RAMS (Regional Atmosphere Modeling System), a regional climate model developed at Colorado State University and widely applied to climate research. Detailed descriptions of LEAF are given in (Walko et al. 2000) it includes prognostic water-energy in multiple layers in the soil column to a user-defined depth, a surface store (ponding and snow), a vegetation store, and a canopy air store.

In the Iberian Peninsula LEAF and LEAF-HYDRO have been used from the pioneering work of Miguez-Macho et al. (2007) who also integrated groundwater into the system. The water table depth is diagnosed based on the soil moisture when it lies within the resolved soil layers. When the depth is deeper, soil columns are extended to the dynamic water table below, thereby acting as saturation boundary conditions and affecting the soil water fluxes above. There is lateral groundwater flow among adjacent cells, leading to divergence from the high ground and convergence with low valleys at multiple scales. The water table, once recharged by rain events or fed by lateral flow convergence, relaxes into rivers within a grid cell through fluxes between groundwater and rivers. These fluxes can be 2-way depending on the hydraulic gradient, representing both losing (i.e., leaking into groundwater) and gaining (i.e., receiving groundwater) streams. River discharge, which is fed by surface runoff and groundwater, is routed out to the ocean through the channel network using the kinematic wave method. The sea level is set as the head boundary condition for groundwater, which allows it to influence coastal drainage.

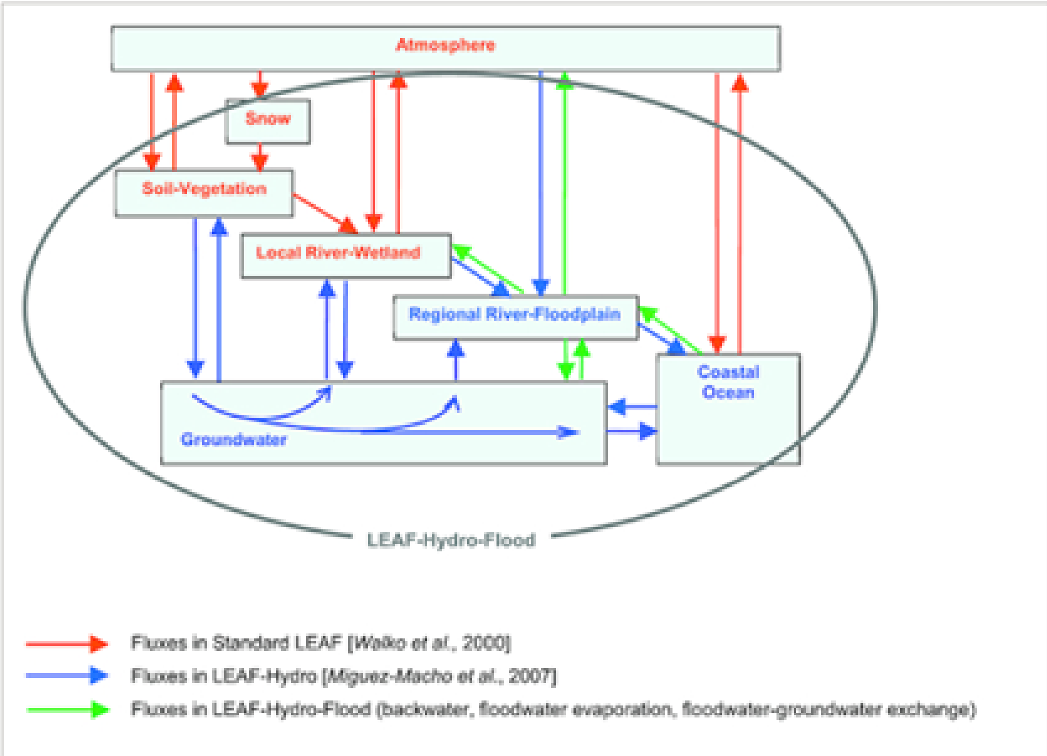


Fig. 6: Model schemes of LEAF and LEAF-HYDRO (Miguez-Macho and Fan, 2012)

Martínez-de la Torre and Miguez-Macho, (2014) applied LEAFHYDRO LSM to model the influence of groundwater on land-atmosphere fluxes due to the support of groundwater to soil moisture via water table and gravity-driven lateral transport. Groundwater and its interactions with land processes is one of the challenging frontiers of hydrology, which consequently, recommends the use of LSMs to evaluate these fluxes. This approach allows authors to evaluate groundwater influence on soil moisture and evapotranspiration fluxes in the Iberian Peninsula over a 10-year period. The estimates are validated with time series of piezometric observations covering different basins of Iberia. Results showed that LSMs produce realistic water tables, shallower in valleys and deeper under hilltops, whose patterns over the basin sustain groundwater–land surface coupling in valleys and flat areas. Authors suggest that water levels show a strong seasonal and interannual persistence of the water table, both on past wet conditions and dry conditions, causing a delay in drought recovery, with remarkable changes on ET compared to the scheme without groundwater interactions. The ET enhancement is larger over the drier southern basins, where ET is water limited than where ET is energy limited. Results also show dry season baseflow is sustained by groundwater mechanisms such as lateral flow originated from accumulated recharge during the wet season.

Quintana-Seguí et al. (2020) uses LEAF-HYDRO and SURFEX-ISBA to simulate drought propagation from precipitation to soil moisture and streamflow for the period 1980-2014 forced by the Spanish SAFRAN and the global eartH2Observe datasets. We produce standardized indices for precipitation (SPI), soil moisture (SSMI) and streamflow (SSI). Results show that the model structure causes important uncertainties in the LSM-based hydrological simulations. Propagation scales for drought regarding both soil moisture and streamflow are overly dependent on the model structure. Authors outline that uncertainty from the forcing datasets have an impact on the results generally of less impact than model formulation.

OTHER LSMs: NOAH, PLEIM & XIU, 5 LAYERS, H-TESSEL

• NOAH Land Surface Model (Chen and Dudhia, 2001) is a model consisting on four soil layers with thicknesses of 10, 30, 60 and 100 cm, and an additional canopy layer. The prognostic variables are soil moisture and temperature in the soil layers, water stored on the canopy and snow stored on the ground. The total soil depth is 2 m, with the root zone in the top 1 m of soil. The lower 1-m soil layer acts as a reservoir with gravity drainage at the bottom. The ground heat flux is again controlled by the usual diffusion equation for soil temperature, but in this model heat capacity and thermal conductivity are formulated as functions of the soil water content. The temperature at the lower boundary (assumed to be 3 m below the ground surface) is specified by the annual mean surface air temperature. The diffusive form of Richard's equation is used as the prognostic equation for the volumetric soil moisture content, where the hydraulic conductivity and the soil water diffusivity are also functions of the soil water content. The total evaporation has three contributions: direct evaporation from the top shallow soil layer, evaporation of the precipitation intercepted by the canopy, and transpiration via canopy and roots. The vegetation fraction is defined in 12 percentage-values for 12 months at each of lat/lon grid points. Landuse/vegetation category is specified from USGS v2 land cover data. Soil thermal properties also depend on soil type (assigned to each cell from a 30″ 17-categories data base). A simple snow and sea ice model are included.

• SFL Pleim & Xiu Model (Pleim & Xiu, 2001).
This model differs conceptually from those described above. Only two soil layers are considered, a thin (1 cm thick) surface layer, and a 1-m deep reservoir layer. The zero-flux condition is imposed at the bottom for both temperature and moisture content prognostic algorithms. Soil temperature is calculated through the force restore method. For the evolution of soil moisture, the same contributions as in Noah LSM are taken into account. Evaporation parameterization is also conceptually analogous to the Noah scheme.

• Simple Five-Layers Soil Model (Dudhia, 1996).
This model uses five soil layers with thicknesses, from top to bottom, of 1, 2, 4, 8 and 16 cm. Below the bottom level, at 31 cm, the substrate temperature is kept constant in a 32-cm thick layer. The transfer of heat follows the one-dimensional simple diffusion equation (the heat flux is linearly proportional to the temperature gradient). The flux convergence is proportional to heating. The parameters that appear in such formulations (soil's thermal diffusivity and specific heat capacity) are constant in time, depending only on the land use/vegetation category which is specified from 25-category 30″ data from USGS version 2 land cover data. Available soil moisture remains constant during the whole simulated period, one for summer and one for winter, but just one of them is used depending on the initial date of the runs. Neither runoff nor canopy transpiration processes are considered in this LSM. Snow cover is treated as any other land use category.

• H-TESSEL (Hydrology revised-Tiled ECMWF Scheme for Surface Exchanges over Land) is the land surface model from ECMWF (Balsamo et al., 2009). The improvements include a new soil hydrology with more realistic runoff, a revision of the snow parametrization and the bare ground evaporation and a monthly varying climatology of leaf area index (LAI) based on MODIS data. The H-TESSEL scheme shows up to six tiles over land: bare ground, low and high vegetation, intercepted water, and shaded and exposed snow) and two over water (open and frozen water), with separate energy and water balances. The vertical discretization considers a four-layer soil that can be covered by a single layer of snow. The depths of the soil layers are in an approximate geometric relation (7 cm for the top layer and then 21, 72, and 189 cm). The soil heat budget follows a Fourier diffusion law, modified to take into account soil water freezing/melting. The energy equation is solved with a net ground heat flux as the top boundary condition and a zero flux at the bottom. An interception layer accumulates precipitation until it is saturated, and the remaining precipitation (throughfall) is partitioned between surface runoff and infiltration. Subsurface water fluxes are determined by Darcy's law, used in a soil water equation solved with a four-layer discretization shared with the heat budget equation. The vertical movement of water in the unsaturated zone of the soil matrix obeys the Richards equation. The top boundary condition is infiltration plus surface evaporation, free drainage is assumed at the bottom, and each layer has an additional sink of water in the form of root extraction over vegetated areas. All these definitions and a few more determine a very complete LSMs usually dedicated to weather forecasting together with other ECMWF models. There is only one application of this model in the Iberian Peninsula by Barella et al., (2017), study detailed in the 2.2 ORCHIDEE section.

These additional models are not applied to studies directly related to drought analysis but were in the origin of LSMs and especially H-TESSEL, NOAH and SFL still have some potential to be used for them, since the following works have evaluated related variables such as temperature trends, of great relevance in the evolution of droughts.

Jerez et al. (2010) conducted a study focus on the comparison of three different land surface models for high-resolution climatic simulations coupled to the mesoscale model MM5 over the Iberian Peninsula. Only two of the LSMs dynamically model moisture (NOAH, Pleim & Xiu models) while in the simplest model (Simple Five-Layers) SM is fixed to climatological values. The study period covers 1958–2002, using the ERA40 reanalysis data. The aim of the study is to evaluates the skill of each model in reproducing mean values and temporal variability of temperature series compared with temperature observations. Greatest deviation was observed for the 5 layers model during summer season, of severe underestimation. The other two performed substantially better and great concordance between the simulated and observed spatial patterns. Dynamic soil moisture parameterization and the more realistic simulation of latent and sensible heat fluxes between the land and the atmosphere of NOAH and XIU explain the better results of these two LSMs.

Jerez et al., (2012) expanded the use of NOAH for the evaluation of climate scenarios, and the influence of changes on soil moisture to the rest of the system variables. Their work assessed the influence of soil moisture on temperature, precipitation and wind over the Iberian Peninsula and climate change scenarios. Results indicated during an increased interaction of SM with atmospheric variables during the summer season. The more severe warming over the inner dry Iberian Peninsula further implies an intensification of the Iberian thermal low and, thus, of the cyclonic circulation. Furthermore, the land-atmosphere coupling leads to the projection of a wider future daily temperature range, since maximum temperatures are more affected than minima. Regarding variability, the areas where the land-atmosphere coupling introduces larger changes are those where the reduction in the soil moisture content is more dramatic in future simulations. Interestingly, stronger low translates into weaker positive signals for convective precipitation. These results highlight the crucial relevance of interactions on the system, especially under transient regimes caused by climate change.

Cross-cutting methodology for the HUMID project

The HUMID project analyses drought using remote sensing and modelled data. It needs a common approach that allows us to study drought processes and their dynamics using different sources of data in a comparable way. Using drought indices is an obvious choice, as this removes all the problems related to biases between data sources. It also allows us to correctly compare the results of different regions.

Calculation of drought indices

Drought indices may need to be calculated at the monthly and the weekly time step, and the methods will not be exactly the same in both cases.

Calculation of monthly drought indices

The proposed methodology to calculate monthly indices is based on the SPI methodology. This index is calculated using monthly data or, alternatively, a time series of the accumulated precipitation for the previous n months, where n represents the scale of the index. A similar operation can be done for soil moisture (SSMI) and streamflow (SSI). We use a nonparametric methodology, which can be applied to different climatic variables, including precipitation, soil moisture and relative humidity, without having to assume representative parametric distributions (Farahmand and AghaKouchak 2015).

Calculation of weekly drought indices

The weekly scale is proposed to study interactions between precipitation, soil moisture deficit and evapotranspiration deficit. The SPI can be calculated at the weekly scale with no issues, just by ensuring that the accumulated period is of four or more weeks (one month or more). For the other two variables, we propose to use the ETDI and the SMDI indices (as defined in previous sections).

Analysis of drought propagation

The methodology proposed to study drought propagation is inspired by Barker et al. (2015):

1. The standardized soil moisture index (SSMI or SSI) is calculated with a temporal accumulation of 1 month.
2. For precipitation, SPI-n is computed for n in [1,2,...,24].
3. For any given grid point, the *nx* scale maximizing the Pearson correlation coefficient between SPI-n and SSMI/SSI is found.

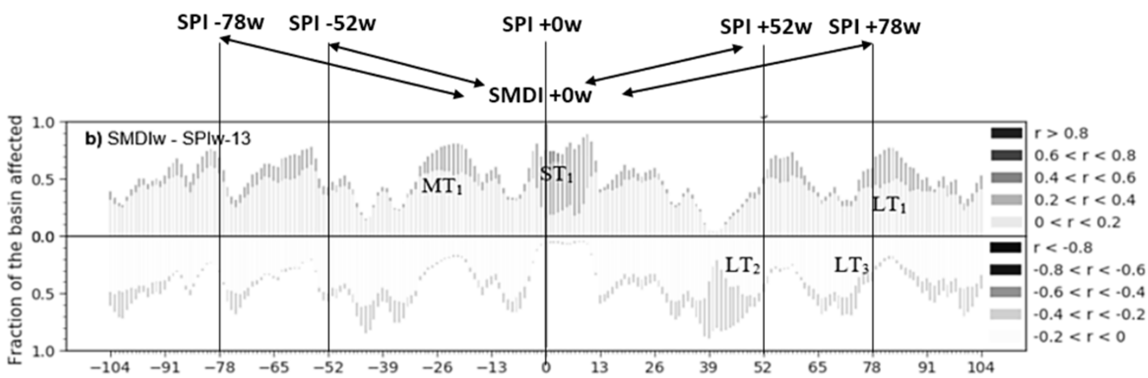
The resulting *nx* can be interpreted as the scale at which drought propagates from precipitation anomalies to soil moisture anomalies. For streamflow, the methodology is mostly the same, with the difference being that the SPI is calculated with the areal mean of the basin precipitation corresponding to the gauging station of the studied streamflow.

Analysis of lags between variables

If in the previous section we presented the dependence of the drought index on the accumulation of preceding precipitation, we might also be interested in exploring the delay in which one variable reacts, respect to the other. For this purpose, at the weekly scale, the time series are correlated with shifts of (-*n*, …, 0, …, *n*) weeks, being *n* = 104 (two years).The period of two years for the analysis of lags is convenient for areas, such as the Mediterranean basin, where multi-annual droughts are recurrent. When the correlations are plotted against the lag time (positive and negative) different peaks will appear which will show lagged effects of one variable to the other. These lags can be computed with the indices with different time accumulations, which adds some complexity to the comparisons but informs about the optimal scale for the identification of the interactions between indices. The analysis of positive and negative lags provides information about the asymmetry of the interaction between the indices (precedence and subsequence). The meaning of the positive and negative correlations helps to interpret the characteristics of the periods of correlations since positive ones indicate periods which tend to stability and negative ones indicate periods of transitional characteristics. The widening of the clusters of correlation (consecutive weeks with similar correlation values) with the increasing period of aggregation of the SPI can be used to understand the memory of the interactions between SPI and other indices corresponding to other variables, such soil moisture or evapotranspiration deficits.

Comparison and validation metrics

To compare standardized indices of the same variable (i.e. soil moisture) corresponding to two different products or to a product and the observations we propose the use of the root mean square difference (RMSD) and Pearson Correlation coefficient (r). The first one accounts for the differences in severity, and the second one accounts for the covariance over time of the two time series. Over large areas, we might be interested in knowing the percentage of the area that presents a certain degree of correlation, and this can be done for different lags. For this purpose, we propose to plot a bar plot which shows stacked bars at each time lag with the proportion of the basin that has a given Pearson correlation coefficient (as shown below). This graph can be improved by indicating only the proportion of the basin that has significant correlations. Additional metrics for the comparison of the interactions between indices can be computed by calculating the percentage of the monthly, seasonal and annual scale affected by certain r Pearson levels of positive or negative correlations. With this procedure there is a tool to compare the relative dominance of certain interactions between indices over others at a specific time scale, which can be useful to identify distinct types of drought from their onset.



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