Remote sensing for drought monitoring in the Iberian Peninsula

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Drought as a data-demanding research field, opportunities of remote sensing

Drought is the natural phenomenon characterized by a persistence of dry conditions in the climatic variables affecting different aspects of the natural or anthropogenic systems. The cumulative impact of anomalies in the climatic variables is the origin of recurrent droughts in Mediterranean climate of the Iberian Peninsula. The origin of the anomalies is the characteristic climatic variability of this type of climate variability (Jalut et al. 1997, Lionello et al., 2005) in the transition between the subtropical and temperate areas, which is a combination of random and repeating climatic patterns such as the seasonal and the circulation patterns (Trigo et al., 2004; Vicente-Serrano, 2005; Vicente-Serrano et al., 2011; Russo et al., 2015).

The temporal evolution of the anomalies explains the propagation of drought from the meteorological variables (e.g. precipitation, of a climatic scope) to the land-based ones such as the soil moisture (of an agricultural or environmental scope) and runoff (of a hydrologic scope) (Wilhite , 2005). Studies often refer to meteorological, agricultural/environmental, hydrologic and socio-economic drought depending on the variables of interest and their impact.

Traditionally, impacts of drought were reported via agricultural and hydrological observations (Martín-Vide and Barriendos, 1995; Cuadrat and Vicente-Serrano, 2002; Dominguez-Castro et al., 2008; many others since these ones) as a major concern for the society (Bentabol, 1898). With the implementation of meteorological and hydrological observations networks during the 20th century, our current climatic databases support systematic analysis of the climate and hydrology over the Iberian Peninsula. However, understanding the interactions between climate, hydrology and all the associated processes of the land-surface interface, such as drought, demands diversifying the sources of environmental data.

Yet, until recently, there were few datasets of variables of difficult, costly or time-consuming direct observation like evapotranspiration and soil moisture. Drought, like many other disciplines, faced important challenges due to the availability and suitability of these often-neglected data (AghaKouchak and Nakhjiri, 2012). Additionally, the perspective of accelerating global change, recommends the intensification of data collection to assess both the ongoing quick changes and past conditions to help speed up our understanding of natural hazards like drought.

The emergence of remote sensing technology during last decades, thanks to its wide range of applications, helps to overcome the limitations of many fields of environmental research, like drought, lacking specific data of sufficient spatial and temporal resolution

(AghaKouchak et al., 2015). The aim of this study is to provide an overview of the contribution of remote sensing applications to the study of droughts in the Iberian Peninsula. The description the chronological sequence of applications and developments among some distinct disciplines such as those focus on climatologic, hydrologic, agricultural and forest drought.

Drought monitoring studies using remote sensing in the Iberian Peninsula

Drought studies using optical data

The use of Remote Sensing (RS) data to investigate soil moisture in the Iberian Peninsula started based on optical data. Pioneering works with optical remote sensing focused on the water availability related to vegetation. Montero et al. (1999) assessed the dynamics of vineyards in La Mancha comparing the phenological status of vines from remote sensing and ground-data with the water related variables such as evapotranspiration and rainfall. The study highlights the small variability of vineyards with the phenological stage due to the low cover values of the vineyard. Only in early summer the vine canopy is dense enough to obtain useful Normalized Difference Vegetation Index (NDVI) variability able to monitor plant availability and vegetation health. The assessment of drought itself using optical data started with Gonzalez-Alonso et al. (2003) who used NOAA-AVHRR data. The study focused on the analysis of the spatial patterns of droughts in Spain from 1987 to 2001. The NDVI index is the one calculated from the AVHRR images. Results show an increasing trend of NDVI anomalies which suggest an increasing prevalence of drought in Spain. The authors highlight the potential of remote sensing for long-term monitoring of environmental variables.

Vicente-Serrano (2006) focused on the evaluation of the effects of drought on the status of natural vegetation and agricultural lands of the Ebro basin using the optical data derived from AVHRR images to obtain Vegetation condition Index (VCI) and NDVI indices, which is corelated with the SPI index from ground-based data. The study reported significant correlations of the VCI index with the SPI index, but with remarkable differences in space and time. Results indicate that most impact of drought occurs during spring and summer, when the role of water availability is the most influential. Spatial differences indicate drought impact largely depends on land-cover and topo-climatic conditions. Pasture, sparsely forested and dry-farming areas the most affected. Forests show the lowest VCI-SPI correlation. The temporal scale between 12 and 6 months, corresponding to the rains of the winter season show the largest influence on the correspondence of VCI to the SPI. The study demonstrates the potential of RS data for environmental monitoring and inaugurates drought analysis with satellite data. Vicente-Serrano et al. (2007) further explored the capabilities of this AVHRR NDVI data in comparison with the SPI index and assess the ground-based data of crop production of barley and wheat in the Ebro Basin. Results in this case indicated the best correlations occur between the indices NDVI-SPI for the one and three-months period which points out the importance of winter periods drought status for crop production. March was the month with highest NDVI-crop production correlation. The study also provides a regression model to predict crop production based on the SPI and NDVI of previous time period. The model integrating both SPI and NDVI information provides the best crop prediction. The study highlights the potential of remote sensing data to support crop monitoring useful for farmers. Lasanta and Vicente-Serrano (2012) used again the NDVI across the Ebro basin, but this time to evaluate land-use changes. This study pointed out that drought periods affected negatively the NDVI values of the most arid areas of the basin, where rain-fed cultivation of olive and vine orchards experience certain decline and subsequent land abandonment.

Lloret et al. (2007) also evaluated NDVI response to drought events with a drought scope from forest sciences. They specifically test the influence of species richness on the resilience of forest canopy to drought of different Mediterranean species. The aridity of the localities is differentiated using the Thornwaite index which may cause some uncertainties. The NDVI from SPOT sensor showed more losses in forests of Pinus halepensis and Quercus Ilex of low species richness. Other species like Pinus Sylvestris and P. uncinata did not show the diversity-drought resilience response of the Mediterranean species and Fagus sylvatica show losses of NDVI with drought in areas of high richness of species. In conclusion, the study indicates that drier localities are more resilient to drought with the increase of species richness while in moist localities the abundance of species might lower the overall drought resilience.

Indirectly related to vegetation response to drought, Udelhoven et al. (2009) explored the lags between rainfall and the NDVI. Areas with the maximum NDVI-rainfall correlations include the southeastern coastal part of the Pyrenees in Catalonia and the rainfed areas of Extremadura, Andalusia and Western Castilla y Leon. Areas with significant delay between rainfall and NDVI values comprise the mountainous areas of all northern Spain, where the lag reaches more than six months. Therefore, the use of the NDVI can also inform about memory processes after rainfall anomalies which indirectly informs about the response times of vegetation to anomalies.

Gouveia, Trigo and DaCamara (2009) put the focus on drought monitoring of vegetation using the NDVI index from the same SPOT imaginery, but in this case in combination with the Soil Water Index (SWI). The area of study was the continental

Portuguese territory from 1999 to 2006. The impact of soil moisture on vegetation dynamics is evaluated analyzing the monthly anomalies of SWI vs. the anomalies of the NDVI. Results show clearly visible anomalies of soil moisture with the SWI that enable predicting subsequent NDVI anomalies. This is particularly true for periods of SWI anomalies during the autumn-winter periods causing big impact on the NDVI of the next spring (drought of 2005). Arable lands seem more drought sensitive than forest during most drought events. Gouveia et al. (2012) expanded their work with the NDVI in 2012 to the Normalized difference vegetation Water Index (NDWI) and Normalized Difference vegetation Dryness (NDDI) indexes to evaluate the combined effect of droughts and wildfires in vegetation of the entire Iberian Peninsula. The study explained the negative effect of drought in the recovery of burnt areas. In the other way around, forest fires tended to occur in areas presenting lower drought stress during spring and early summer months which highlights the role of fuel availability in fire occurrence. The authors highlight the capabilities of remote sensing to monitor vegetation status in almost near real-time which is of great value for wildfire prediction.

In 2010, Rossi and Niemeyer from the European Drought Observatory started publishing results of Combined Drought Indicator (CDI) which also integrated the monitoring of the status of vegetation in relation to drought via de fAPAR index (Sepulcre-Cantó et al., 2012).

Sangüesa-Barreda et al. (2014) started the use of the SPEI index (Vicente-Serrano, Beguería and Lopez-Moreno, 2010) in combination with the NDVI and dendrochronological information to evaluate the impact of defoliation from forest pests in combination with drought. They find certain coincidence of climatic stress and defoliation years which requires further analysis of the correlation between these impacts and longer series of data. They also remark the weaker impact of defoliation than drought in tree ring growth. Moreover, they indicated that specific drought indicators such as the case of the SPEI are required to distinguish the relative impact of climatic stress apart from defoliation on the NDVI losses. Camarero et al. (2015) additionally evaluated the influence of timing and severity of drought in the growth response of Quercus Ilex. They use remotely sensed NDVI and Normalized Difference Infrared Index (NDII) to infer the loss of forest productivity with drought. Tree growth sues dendrochronology. 2005 and 2012 droughts generate the most impact on tree growth, causing the loss of synchronicity of the primary and radial growth and defoliation events. Remote sensing and primary growth were coupled through time, whereas secondary growth was uncoupled. Secondary growth showed legacy effects. Defoliation can be a noisy proxy of drought stress. The study remarks the influence of drought timing and intensity on forest resilience to drought while highlights the need to disentangle the trade-offs between the non-linear responses of vegetation to drought stress. Vicente-Serrano et al. (2015) explored the Global Monitoring and Mapping Studies (GIMMS) dataset which includes remote-sensing NDVI data at global scale to evaluate drought variability and land degradation in relation to the periods of drought identified with the SPEI index. Despite the positive evolution of NDVI in most semi-areas of the world, the NDVImax was the most correlated index with drought variability, indicated by the SPEI drought index. The trends in the NDVI values, especially in some areas like the Sahel, South Africa and Australia cannot be explained by drought variability alone which suggested vegetation effects obscure the drought-land degradation interaction. The authors indicate the need to improve our understanding of vegetation response to drought in semi-arid areas, which can be non-universal and strongly influenced by multiple natural and anthropogenic factors.

Hunink et al. (2015) also explored the use of remote sensing vegetation indices to study groundwater use in agricultural irrigated areas of perennial and seasonal crops. Crop intensity and irrigation water applied (IWA) were calculated using NDVI from MODIS and in-situ data. The IWA index correlates well with the recorded irrigation water used in the fields except for periods of drought, when salt leaching irrigation is active. Thus, during droughts, groundwater use increases considerably, especially for perennial crops. The study outlines the resolution of MODIS limits monitoring irrigated lands, and may overlook the spatial heterogeneity of the crop's mosaic. Authors indicate that this NDVI analysis neglecting soil evaporation losses is acceptable over areas of drip irrigation but may not be reliable where soil evaporation is a significant process. Since the use of groundwater increases during drought years, monitoring groundwater extraction requires especial attention from water managers in drought-prone areas. The study highlights the worth of using this approach of monitoring aquifer use with remote-sensing based indices in areas of poor data of groundwater or irrigation consumption. Contreras and Hunink (2016) published preliminary results of the development of Infosequia as the first remote sensing-based drought monitoring system of Spain. The system includes monitoring of the NDVI, LST and their combination. They proposed 4 warning levels for drought's severity evaluation. Infosequia aimed to follow the trends of the anomalies of the indices to generate drought reports available for stakeholders about the sensitivity and resilience of their natural and agricultural systems.

Another application of remote sensing of vegetation with an hydrological scope was the study of Jodar et al. (2017), who evaluate water resources in the semi-arid mountain range of Sierra Nevada using optical dat. They developed the VI-ETo model that integrates information from the Soil Adjusted Vegetation Index (SAVI) obtained from Landsat 8 images to evaluate the evapotranspiration consumption of different types of vegetation. The combination of the VI-ETo model with lumped-tanks model HVB allows to estimate the discharge in the basin and planning the availability of water resources. Remote sensing helps differentiating the spatial patterns of evapotranspiration while modelling allows considering the effect of important processes such as infiltration and recharge. Consequently, the remote-sensing – modelling approach is of great value to improve the understanding of processes in ungauged basins.

Back to the use of optical data for the evaluation of drought resilience of vegetation, Gazol et al. (2018) focus again on the NDVI index derived from remote sensing data to assess forest resilience to drought at the scale of the Iberian Peninsula using the SPEI index and dendrochronological data (using the Tree Ring Width growth index (TRWi)). Four components of tree resilience were studied: relative resilience, resilience, recovery and resistance. Gymnosperm species showed less resistance but more capability to recover from drought than deciduous angiosperms from temperate areas. Species may show gradients of drought resistence-resilience depending on their origin. In respect to remote-sensing data, results showed that the in-situ data correlates better with the SPEI than the NDVI index. Guirado et al. (2018) inaugurated the use of Sentinel 2A data to generate NDVI maps of the arid region of the Gata-Nijar natural park in order to evaluate the location of drought-resilient vegetation over the impervious geology of this very arid area. The study proves the apparent drought resilience of certain vegetation communities has its origin on their tendency to grow over areas of fractures where groundwater assists their survival in an arid environment. The study illustrates the advantages of geophysics and remote sensing to approach the analysis of vegetation resilience to drought and especially groundwater dependent ecosystems, whose role in the bioma are of key importance in some arid environments of the Iberian Peninsula. Peña-Gallardo et al. (2018) focused on the possibility of NDVI alone to support the evaluation of de decay of forested areas due to drought in the Iberian Peninsula and Balearic Islands using the Palmer drought index versions PDSI, PHDI, Z-index and the PMDI along with the SPI, SPEI and SPDI drought indices. The study highlighted how the multi-scalar drought indices such as SPI and SPEI outperform the uni-scalar ones of the Palmer family. Tree ring data was used too (in the form of the TRWi index) to evaluate the impacts of drought in the tree species. Temperate and montane species seem less correlated to drought indices that the thermophile species. The longer time span of correlations in coniferous and thermophilic species denoted their responsiveness and adaptability to drought. The role of climatic and soil characteristics in the heterogeneity of correlations with drought indices between and within the species was also noticed. Late spring drought conditions are the most influencing on NDVI while summer months drought conditions play a major role on tree ring growth. All in all, simple remote sensing data such as the NDVI in combination with drough indices proved of great value to study forest sensitiveness to drought.

Vicente-Serrano et al. (2019) expanded on this use of the NDVI together with the database of the SPEI drought index for the evaluation of vegetation activity depending on drought conditions for different land-use types. The study highlights that more than 90% of the area of Spain exhibits significant correlations between the NDVI and the SPEI during dry summers, which indicated the interannual variability of drought governs vegetation activity in the Iberian Peninsula, particularly in arid regions, which was consistent with the bigger responsiveness of vegetation to drought status reported in previous works. Differences in the timing of the correlations SPEI-NDVI were identified between different land cover types indicating the importance of the characteristic phenology of the vegetation of each land-cover type. Herbaceous crops show the highest NDVI-SPEI correlation. Forest and natural vegetation areas respond to longer timescales than pastures and crops due to their different reliance strategies to drought with difference depending on characteristics of the basin and the vegetation.

Irrigation areas respond to timescales of correlation depending on water management policies. Thus, the study outlines remote sensing data and drought indices facilitate analyzing how the different land-cover types respond to drought at different time scales depending mainly on aridity.

Drought studies using microwave and radar remote sensing

These first decade of the century led to the exploration of remote sensing Synthetic Aperture Radar data (SAR) to monitor overexploited aquifers, which is closely related to drought management due to the dependence of many areas on groundwater when surface water resources decline. Tomas et al. (2005) used differential SAR interferometry in the Segura River to evaluate ground subsidence caused by aquifer overexploitation. Correlation has been observed between the interferometry and the ground-based data. Despite spatial differences, the remote sensing data provide useful spatial estimates of the subsidence at low cost. Authors highlighted the potential of this technique for monitoring areas without ground-data, especially when caused by aquifer exploitation in rural areas. Gonzalez and Fernandez (2011) expanded this exploration of the subsidence of the Vega Baja of Segura River with SAR data in view of the increasing overexploitation of the aquifer. The authors indicated the need to integrate this type of remote sensing data to the monitoring of aquifer in drought-prone areas to improve water management policies.

However, the turning point towards widespread use of this type of remote sensing data occurred with the launch of the Soil and Moisture and Ocean Salinity mission (SMOS) of ESA (Kerr et al., 2010). SMOS provided the first soil moisture datasets derived from passive microwave data in 2010. This dedicated soil moisture mission opened multiple possibilities for applications interested in soil moisture monitoring, such as drought monitoring. However, since the initial data products from the SMOS sensor provided too coarse spatial resolution for regional studies, several groups pioneered in the development of tools to downscale SMOS data to facilitate its application in disciplines demanding more spatial resolution.

Development of high-resolution soil moisture remote sensing data for drought monitoring

Piles et al., (2011) began the attempts to downscale SMOS data with data from the Iberian Peninsula. The study focused on the use of visible and infrared data sources used in the generation of the NDVI index and Land Surface Temperature (Ts) from MODIS imagery to downscale the SMOS data. The group test the universal triangle algorithm to downscale both the SMOS data and an equivalent airborne radiometric dataset (ARIEL). The downscaling method seemed able to effectively capture the spatial variability of soil moisture at 10 and 1 km. Piles et al (2013) evaluated the reliability of this SMOS disaggregated data using TERRA/AQUA MODIS datasets, but this time contrasting results with ground-based measurements from the REMEDHUS soil moisture network which has been repeatedly used to investigate soil moisture, remote sensing products and drought in the Duero Basin (Martinez-Fernandez's hydrology group at University of Salamanca (USAL)-CIALE). The study indicates the downscaling of SMOS data with MODIS provides soil moisture data that compares well with in-situ soil moisture measurements. When comparing remote sensing with in-situ data, upscaling of the in-situ data, such as the one form the REMEDHUS network, is usually required.

A more physical approach to downscale SMOS data was proposed by Merlin et al. (2012) to define their disaggregation algorithm DISPATCH (DISaggregation based on Physical And Theoretical scale Change) which was finally applied over the Iberian Peninsula in the study of Merlin et al. (2013) together with ASTER and Landsat-7 data for evaluation of the potential of all these remote sensing data for soil moisture monitoring at 3km and 100m resolution. The study showed how the application of disaggregation methods such as DISPATCH provide robust high-resolution soil moisture data which compares very well with in-situ observations, with a small tendency to underestimate soil moisture during dry events. The study concludes that disaggregated datasets of soil moisture provided by DISPATCH have great potential for multiple environmental monitoring purposes such as drought monitoring.

Sanchez-Ruiz et al. (2014) further explored the combination of infrared satellite data with SMOS disaggregated data from Piles' group to evaluate the suitability of infrared NIR/SWIR/TIR data for the characterization of land-surface temperatures (LST), which can be used in downscaling algorithms of SMOS. The study compares the possibility of using NIR and SWIR indices of water content of vegetation (NDWI from three different infrared ranges) with the NDVI (all from MODIS) as proxy to improve the resolution of SMOS data up to the MODIS spatial resolution (500m). Results show similar performance for the four indices: NIR, SWIR, LST and T_B. The disaggregating approach is particularly robust in periods of high vegetation activity. Other groups made use of the pioneering desegregations of soil moisture data for drought monitoring described in previous paragraphs.

Recent studies started to incorporate SMAP data into soil moisture analysis. Ojha et al. (2019) explored the disaggregation of SMAP SM data using MODIS data to disaggregate first from 36 km to 1 km resolution with the $DISPATCH_{Lin}$ algorithm and later on with from 1km to 100m resolution using the Landsat data and $DISPATCH_{Exp}$ algorithm. The study studies how the two-step disaggregation improves the robustness of the SM estimates more than the single-step approach. The correlation coefficient between the disaggregated 100m SM estimates and the in-situ data range from 0.5 to 0.9 for most of the sampling dates. The study also proposes a method to reduce artifacts in the disaggregation. Authors warn about the sensitiveness of DISPATCH to cloudiness while suggest the potential synergies with radar-based data. The study opens the path to applications with high resolution SMAP data for drought monitoring and other hydrological purposes.

Portal et al. (2020) provided a comparative analysis of six operational SSM derived from SMOS and SMAP to diagnose their differences and suitability for applications in the Iberian Peninsula. The datasets are compared with in-situ data from the REMEDHUS network of the USAL. The two distinct approaches for disaggregation of the SSM data: the microwave-optical one of SMOS/ERA5/MODIS vs. the active-passive microwave one of SMAP/sentinel-1 are evaluated. Results show an overall agreement of the products between them and with the in-situ data. SMAP products provide slightly higher SM values than SMOS. SMAP and SMOS differ especially during summer when SMOS differs more too from in-situ data. The largest disparities occur in the forested areas which is consistent with previous reports of RS SM products inaccuracy in densely forested areas. The C-band microwave signal of SMAP seems to perform worse than SMOS L-band over forests. The study identifies the need to further downscale of the products to capture the small-scale heterogeneity of soil moisture patterns, particularly for irrigated areas.

Yet, improvement in the disaggregation methods are still being developed. Stefan et al. (2020) presented an update of the calibration methods of the DISPATCH disaggregation algorithm based on soil evaporative efficiency. The study tests a new non-linear temporal calibration of DISPATCH. Results indicate that the previous linear calibration scheme was generally robust when using a daily calibration, while the non-linear approach systematically displays better results even using the year calibration. The temporal correlation coefficients increased from around 0.2 to 0.5 with the non-linear approach over Spain. The study suggest that the non-linear calibration scheme fits better the non-linear response of soil evaporative efficiency to soil moisture. Thus, adopting non-linear calibration can have significant positive impact on the performance of SMOS disaggregated datasets using the DISPATH algorithm.

Studies exploring remote sensing and in-situ soil moisture estimates

Scaini et al. (2015), though, already applied non-disaggregated data from the SMOS L2 products to generate soil moisture anomaly maps to investigate drought over the REMEDHUS soil moisture network with SPI and SPEI indices. The study concluded SMOS data correlated better with the meteorologically-derived SPI and SPEI indices compared to in-situ data. Differences are attributed to the tendency of remote sensing to captures higher soil moisture distributions in the very surface, which affected by soil characteristics, become less uniform with depth where in-situ measurements are collected. The study also indicates the convenience of adopting the SPEI to integrate the important contribution of evapotranspiration on the evolution of drought and highlights the potential of SMOS data for the evaluation of droughts at the regional scale.

In the study of Gonzalez-Zamora et al., (2015a), the Hydrology group of USAL deepened in the investigation of the applicability of SMOS by comparing the previously used SMOS L2 dataset with the improved SMOS L3 dataset developed by the Barcelona Expert Center (Piles' group) over the REMEHEDUS and InfoRiego soil moisture monitoring networks. The study indicated that both L2 and L3 SMOS series had larger dynamic range than the in-situ data, while the L3, despite being of similar coarse resolution, provided better accuracy than the L2 data series. Lags between in-situ and SMOS soil moisture series were also noticed, being SMOS data the most reactive to rainfall or dry-down events. SMOS results still show the tendency to underestimate soil moisture during dry periods. The study highlights the problematic correspondence of heterogeneity-biased in-situ observations with the homogeneity-biased radiometric observations of SMOS. The same USAL group evaluated other remote sensing products apart from SMOS. Sanchez et al. (2015) assessed the capability of airborne GNSS-R sensor together with Landsat-8 to estimate the soil moisture status at the local scale. The evaluation indicated the opportunities of the relationship between reflectivity of GNSS-R and surface temperature and vegetation indexes from Landsat to estimate soil moisture, given the good correlation between the estimations and the in-situ measurements of the REMEDHUS network. Gonzalez-Zamora et al. (2015b), explored too the potential of Aquarius/SAC-D mission together with SMOS to estimate soil moisture over the REMHEDUS and Inforiego soil moisture networks. SMOS generally outperformed Aquarius results due to its better spatial resolution, which indicated that SMOS is the preferable data source for soil estimates from the global to the regional scale.

In view of the possibilities of these data sources for environmental monitoring, particularly in an agricultural scope, Martinez-Fernandez (2016) assessed the usefulness of SMOS L2 for the monitoring of drought with the Soil Water Deficit Index (SWDI). The SWDI from SMOS L2 data was compared with the SWDI obtained from the in-situ data of the REMEDHUS network. The estimation of the field capacity and wilting point from SMOS percentiles of value induced less correspondence between the in-situ and remotely sensed SWDI than when in-situ parameters of pedotransfer functions were used to refine the SWDI. The refined SWDI showed very good agreement with the Crop Moisture Index (CMI) and the Atmospheric Water Deficit (AWD) also used for comparison, which indicated the reliability of SMOS-derived indices such as the SWDI for agricultural drought monitoring. To expand the exploration of this soil water indices, Gonzalez-Zamora et al. (2016), investigated the Plant Water Availability (PAW), which cannot be directly measured from remote sensing. SMOS data do not provide enough information to evaluate the PAW, but the use of a proxy to determine water content in depth with the information about the soil water travel time from the Soil Water Index (SWI). The results of PAW from SMOS showed good agreement with the ones of the in-situ data from the REMEDHUS soil moisture network. The estimates of PAW with SMOS closely follow the dynamics of soil moisture along both dry-down and rewetting events and only a small underestimation was noticed, in line with previous studies reporting some underestimation of soil moisture values. The study outlines the need to explore more approaches to obtain root zone estimates from surface soil moisture data.

Sanchez et al. (2016) defines a new Soil Moisture Agricultural Drought Index (SMADI) to integrate the surface temperature (LST) and NDVI from MODIS and the soil moisture (SM) observations from SMOS mission to explore the inverse relation between these variables. The proposed SMADI Index aimed to combined soil moisture and temperature conditions including the lag of vegetation to changes in the conditions. The study evaluates the performance of the SMADI Index in comparison with other common drought indices used in the Iberian Peninsula. The best version of the SMADI index was the one combining SMOS data with the daily LST and NDVI from SMOS. The Index agrees to a great extent to the CMI and SWDI indices and slightly lower with the SPI at the local scale of the REMEDHUS study area but losses agreement with the increasing spatial scale. Despite these differences, SMADI was anyway able to capture the duration and intensity of the drought evets. The NDVI proxy seems to support the surface limitations from SMOS data while capturing part of the delayed vegetation response to soil moisture changes. Additionally, the SMADI index downscales the SMOS coarse spatial resolution (20km) to the resolution of MODIS (500m) which increases its suitability for practical applications. Thus, the study highlights the worth of the synergies between the optical and microwave remote sensing data on the definition and use of drought indices. Sanchez et al. (2017) also tested the SMADI index together with the CMI, SWDI and the VegDRI indices at the global scale with encouraging results of the suitability of applying the RS-based SMADI index at a global scale. Pablos et al. (2017) further explored the latter study applied to the study area of the REMEDHUS, Inforiego and AEMET networks over Castilla y Leon region of Spain. In this case, the SMADI index was compared also to the SMDI, SWetDI, apart from the previous CMI and SWDI. The SMOS data used was already the downscaled SMOS BEC L4 dataset along with the MODIS SR and LST data. The study outlined the higher correlation coefficients of the SMADI and SWDI CMI and especially the SMDI and SWetDI when compared to the in-situ data-based indices AWD and CMI. The SWDI agreed with the AWD when identified periods of drought, and the SMADI, SMDI and SWetDI with the CMI. The SMDI and SWetDI indices did not show any spatial artifacts due to soil parameters while both the SMADI and SWDI experience some bias to moderate and extreme drought respectively. The study outlines the convenience of using the SM over the SM anomalies when seasonality is an important aspect of the analysis of drought, such as in agricultural droughts. Pablo et al., (2018a) expanded the assessment of SMADI and SWDI indices for agricultural drought assessment using remotely sensed root-zone soil moisture data obtained applying the Soil Water Index to the SSM SMOS data. The two indices were compared to the in-situ based AWD and CMI indices of the REMEDHUS/Inforiego/AEMET network in Castilla y Leon. The study provided promising results on the suitability of SMADI and SWDI to characterize root zone soil moisture when the lagged response of the soil moisture transmission with depth is provided with indices such as the SWI.

Pablos et al. (2018b) started the evaluation of SMAP products for root zone soil moisture evaluation in Spain. The study compared the SMAP-CESBIO L4 RZSM, SMOS-BEC SWI and MODIS ATI SWI over the REMEDHUS area. The SMOS products showed a tendency to underestimate SM in comparison with in-situ data, while SMAP tended to overestimate them. The different parametrization of the SWI model to adapt the SSM to the RZSM did not seem to impact the results. Regarding the spatial characterization of RZSM, SMOS-BEC product had the best spatial resolution but SMAP better identified the variability between wet and dry regions. The most densely forested areas of the NW Iberian Peninsula challenged the estimates from the optical MODIS ATI SWI in comparison with the good performance of the microwave products of SMAP and SMOS, but the performance of this optical RZSM product was good compared to the SM dedicated microwave missions.

Studies exploring remote sensing soil moisture data included in databases

Chaparro et al., (2016) used SMOS data together with temperature trends to evaluate drought impact on forests, in particular forest fire activity over the entire Iberian Peninsula. The analysis identified clusters of wildfire activity during years of recurrent soil moisture dry anomalies and high temperatures. More importantly, their study found the importance of pre-conditions on wildfire occurrence, particularly during summer and early autumn. Furthermore, the study exemplifies the suitability of surface soil moisture data to evaluate drought beyond the hydrological or agricultural scopes. Similar applications in research of forest droughts like Martinez-Fernandez et al. (2019) also used SM data but not from SMOS but derived from the optical (ESA CCI) or mixed passive-active sensors (ESA CCISM). The purpose of the study was to test the suitability of these databases to evaluate drought affection to tree growth in the east of the Iberian Peninsula. The series from CCISM proved able to track SM in the Mediterranean forested environments of the study and to provide promising evidence of the correlation of forest growth with SM compared to correlation analysis with other variables such as precipitation.

Studies like the one of Lines, Werner and Bastiananssen (2017) incorporated the study of soil moisture using databases like the Climate Change Initiative (CCI). In this case, multiple remote sensing datasets focusing on different variables (indices) of interest for drought monitoring such as precipitation (SPI), evapotranspiration (SPEI), land-surface temperatures (LST), vegetation health (NDVI) and gross primary production (GPP) were tested along with the soil moisture of the CCI dataset. Mostly MODIS data was used for the indices, while precipitation and soil moisture came from the CHIRPS and CCI databases. The remote sensing datasets were tested in comparison with in-situ data. The study reported the best-correlation anticipation relationships of drought for the SPI, the NDVI and evapotranspiration. Soil moisture and land-surface temperature offer less anticipation while gross primary production showed only acceptable correlations in some rain-fed areas. The study highlighted that media records provide useful data for the reconstruction of drought events and that remote sensing datasets allow managers anticipating these reports especially when using the SPI, SPEI and NDVI. In-situ hydrometeorological data anticipates drought even better than remote sensing. Thus, remote sensing proved robust to identify the ground-observations about the anomalies in the drought indicators and has potential to assist water managers under drought scenarios.

The study of Gonzalez-Zamora et al. (2019) from USAL's group also assessed the performance of SM estimates from the Climate Change Initiative (CCI) database in comparison with SMOS L2 and the in-situ dataset REMEDHUS. Results point out the good agreement between the estimated SM from CCI and from SMOS and in-situ data, particularly over forest and agricultural lands while over pastures larger uncertainties were identified. The study further analyzed a version of the CCI database with integrated SMOS data showing its convenience to improve the accuracy of the CCI database and its applicability for environmental monitoring. Given the recurrent use of in-situ data of the REMEDHUS network of USAL's group, Sanchez et al. (2020) presented an analysis of the performance of some available methods for upscaling the in-situ SM data to be compared with coarse remote sensing SM data. The methods compared were from the inverse distance weighting to the physically parametrized geostatistical methods of SVM and EBK (non-parametric regression models). Results indicate that the increasing complexity of the methods does not increase the accuracy of the averaging while might be severely impacted by site-specific conditions.

Studies exploring remote sensing and modelled soil moisture estimates

The study of Gumuzzio et al. (2016) began the evaluation of the performance of SMOS data to estimate soil moisture in comparison with modelled data. In this study the model was the semi-analytical Soil Water Balance Model Green-Ampt (SWBM-GA) (Brocca et al., 2008) following the benefits of comparing remote sensing and modelled estimates of soil moisture for the validation of SMOS data products. Both the SWBM-GA model and the SMOS L2 estimates provided satisfactory estimates of soil moisture compared to the in-situ observations. The study also highlighted the capabilities of models to assist the evaluation of soil moisture at multiple scales with high-resolution.

Polcher et al. (2016) also provided insights about the convenience of testing the modelling capabilities for soil moisture estimation in comparison with remote sensing data from the SMOS mission, but in this occasion the model used is a land-surface model: ORCHIDEE (ORganising Carbon and Hydrology In Dynamic EcosystEm) ((De Rosnay & Polcher, 1998; Krinner et al., 2005). REMEDHUS network again was the testing site for the estiamtes from these modelling and remote sensing data sources. The analysis of the spectral slopes of both datasets suggested that SMOS may observe a shallower and faster soil moisture reservoir than the model does. The study also highlighted the poor correlation between SMOS L2 and ORCHIDEE surface soil moisture spatial estimates of surface soil moisture, while results also indicated that both remote sensing and modelling estimates experience issues with the temporal inertia of the soil moisture. Apparently, the patterns of low correlation between the remote sensing and modelling estimates have its origin in slow varying spatial structures that are not related with rainfall-driven variability, which are in SMOS but are not reproduced by ORCHIDEE.

In view of the limitations of concern in the abovementioned study, Barella et al. (2017) investigated the differences between the remotely sensed brightness temperatures of SMOS and the land surface models ORCHIDEE and H-TESSEL when using the radiative transfer models of CNEM over the Iberian Peninsula. The study highlighted how the brightness temperatures show good temporal agreement but not so much spatial consistency. The brightness temperature datasets were analyzed with an orthogonal function analysis to identify sources of such inconsistencies in the estimates of the LSMs. A structure of brightness temperature bias was identified in the southwest of the Iberian Peninsula but no reason was found behind the phenomenon. Thus, the study highlighted the importance of finding the source of this spatial inconsistency and several candidate analyses were proposed to solve the issue, being the SSM range limits linked to saturation artifacts the likely cause of the identified structure. Consequently, despite LSM capabilities in the estimation of SM estimates, improvements are required to increase their spatial accuracy, which remains behind the robustness of RS SM estimates.

The capabilities of land surface models (LSM) to evaluate soil moisture in comparison with remote sensing data were explored too by Escorihuela and Quintana-Seguí (2016). In this case, the LSM was the Météo-France model SURFEX-ISBA. The remote sensing datasets focus of the comparison: ASCAT, AMSR, SMOS and SMOS high-resolution in a Mediterranean Environment of Catalunya, Spain. The study provides a complete overview of the performance of soil moisture estimates derived from these data sources at different land cover classes such as drylands in contrast to irrigation plots. The study rises awareness about the need to standardized data normalization methods to reduce its impact on the robustness of results. Differences in the temporal resolution of each dataset challenge the normalization methods. Results revealed generally consistent between the LSM SURFEX-ISBA and the remote sensing estimates from SMOS, ASCAT and AMSR. Both remote sensing and modelling SM estimates face difficulties to identify small irrigation plots in comparison to drylands. Among remote sensing data sources, SMOS experience a downgrade of accuracy next to the sea and in some rough areas while ASCAT is limited in natural vegetation areas and AMSR-E LPRM displays a cyclical vegetation effect. The study concludes that SMOS high-resolution is the preferable remote sensing product due to its lack of artifacts related with vegetation which validates it too for drought monitoring and agricultural monitoring, including at irrigated areas.

Khodayar et al., (2019) explored the synergies between SURFEX-ISBA and downscales SMOS L4 data (1km resolution) together with the in-situ data from a dense soil moisture network over the Valencia SMOS anchor-station. This study outlined the capability of LSMs to characterization the temporal evolution of SM while indicates their remaining limited accuracy of SMOS L4 compared to the previous versions of L3 and L2 on the identification of the spatial patterns of SSM, which was reported as accurate in other anchor stations such as the REMEDHUS one. The temporal analysis indicated that the accuracy increases during autumn and winter months compared to the spring and summer ones. The study also reflected the convenience of initializing the model with disaggregated SMOS L4 data products in order to improve the spatial characterization of SSM. The study indicated the need of more anchor stations to improve the validation of SMOS products. Unfortunately, the Iberian Peninsula does not have a dense soil moisture monitoring network like the United States of America where Reichle et al., (2017) conducted a large-scale analysis with multiple anchor-stations for the American counterpart of SMOS L4, the SMAP L4 product.

Synthesis

Drought analysis, methods and studies diversified notably during the last decade largely thanks to the increasing availability and variety of remote sensing products. This study summarizes chronologically the most relevant works on droughts in the Iberian Peninsula using the two main families of remote-sensing products: optical and microwave-based products. The optical products from which multiple vegetation indices can be derived where the basis for a wide range of studies focusing on the impact of drought on vegetation status. Therefore, most of these studies provide an indirect characterization of drought based on the response of vegetation to the stress conditions of the anomalous dry period. Given the limitations of such indirect approach, drought research prioritized monitoring soil moisture to characterize drought when dedicated soil moisture products became available with the launch of the SMOS mission. Soil moisture monitoring, though, required the downscaling of the original data of very coarse resolution (tens of kilometers) to a suitable scale for the intended hidrological, agricultural and environmental analysis of drought. Two main downscaling approaches provided several datasets at kilometer scale able to overcome the resolution limitations. Several groups led the exploration of these downscale datasets in the Iberian Peninsula mainly in comparison with in-situ soil moisture data or in comparison with modelling soil moisture estimates. Both approaches addressed interesting research gaps about the investigation of soil moisture for drought analysis while revealed the synergies between remote-sensing, in-situ and modelling data. Consequently, this study underlines the worth of exploring the progressive integration of these three main sources of data to further improve our understanding of drought.

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