



## Surface moisture and temperature trends anticipate drought conditions linked to wildfire activity in the Iberian Peninsula

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### Abstract

In this study, drought conditions involving risk of fires are detected applying SMOS-derived soil moisture data and land surface temperature models. Moisture-temperature (SM-LST) patterns studied between 2010 and 2014 were linked to main fire regimes in the Iberian Peninsula. Most wildfires burned in warm and dry soils, but the analysis of pre-fire conditions differed among seasons. Absolute values of SM-LST were useful to detect prone-to-fire conditions during summer and early autumn. Complementarily, SM-LST anomalies were related to droughts and high fire activity in October 2011 and February-March 2012. These episodes were coincident with abnormally anticyclonic atmospheric conditions. Results show that combined trends of new soil moisture space-borne data and temperature models could enhance fire risk assessment capabilities. This contribution should be helpful to face the expected increase of wildfire activity derived from climate change.

**Keywords:** Wildfires, soil moisture, surface temperature, anomalies, SMOS, fire risk assessment.

### Introduction

Wildland fires have an important influence on different facets of the Earth system such as vegetation distribution, climate, and carbon cycle [Bowman, 2009], and they are inherent to the dynamics of several ecosystems. Despite this significant natural role, wildfires have negative impacts in environmental, economic and social terms [FAO, 2006]. The magnitude of these impacts is related to the number of fire outbreaks, the fire severity, and the fire spread which in turn are linked to different factors, generally classified in four categories: anthropogenic causes, vegetation, topography and weather. Humans directly or indirectly occasion a major part of fire ignitions in different regions of the world [FAO, 2006], and modify fire regimes changing the availability, continuity and distribution of fuels principally due to land use changes, increase on wildland-urban interface areas [Radeloff et al., 2005; Syphard et al., 2008], and systematic fire extinction [Cohen, 2008]. As a result, the main

vegetation characteristics determining fire spread and intensity are not only linked to natural patterns, but also to human-related factors. At a local scale, vegetation distribution also depends on topography, which conditions wind effects [Whelan et al., 2005]. At regional scales, atmospheric situations determine the key weather factors influencing fires, which are principally wind, precipitations, air humidity, and temperatures [Pereira et al., 2005; Trigo et al., 2006; Amraoui et al., 2014]. The importance of these weather-related variables is crucial to fire ignition and behaviour [Whelan, 1995].

Nowadays, the human-induced global change is leading to an increase on number and intensity of droughts, and to more extreme temperature events. As a result, present climate scenarios forecast a rise in the number of fires during the present century due to drying of vegetation fuels [Settele et al., 2014; Oppenheimer et al., 2013]. Temperatures and rainfall determine the water content of combustibles, especially of litter, which in drought conditions is very dangerous due to its high flammability [Chuvieco et al., 2004]. Actually, fine fuel water content is widely used as a key variable in the most common fire risk models, such as the Fire Weather Index (FWI; [Van Wagner, 1974, 1987]), the National Fire Danger Rating System [Deeming et al., 1977; Bradshaw et al., 1984] and the McArthur Forest Fire Danger Index (FFDI, based on [McArthur, 1967]).

Understanding the coupling among drought, water content of fine fuels, and forest fires is essential in the fire risk study framework and needs of an accurate monitoring of soil moisture. In that sense, satellite estimates of soil moisture are globally available and can be applied to fire risk prediction. First approaches in this research line reported two examples of moisture determining the evolution of fire events. Firstly, Bartsch et al. [2009] used soil moisture measurements from Earth Observation Satellites (ERS-1/2) and concluded that wet soils limited the spread of forest fires in Siberia, and that most fire outbreaks (80%) occurred in dry soils during summer. Secondly, Forkel et al. [2012] also observed that remotely sensed soil moisture was a determinant variable in the evolution of extreme forest fires in the Lake Baikal region (central Siberia). In the last case, the authors used moisture information from the Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E).

Recently, important scientific resources have been invested to new missions specially dedicated to soil moisture sensing [Oschner et al., 2013] which provide more accurate estimates of moisture in most parts of the world. These missions are the satellites Soil Moisture and Ocean Salinity (SMOS; [Kerr et al., 2010]) and Soil Moisture Active Passive (SMAP; [Entekhabi et al., 2010]), which open a path forward in the study of soil moisture applicability in early warning systems of natural hazards (e.g. forest fires). Both platforms operate at the protected L-band (1.4 GHz), the optimal microwave frequency for soil moisture retrievals [Kerr et al., 2010]. In particular, SMOS has already provided more than six years of surface soil moisture measurements at global scale since its launch in November 2009.

The applicability of SMOS data on forest fire prevention has been already studied over the Iberian Peninsula. Specifically, the studies presented in [Chaparro et al., 2014, 2015, 2016] have reported that the use of SMOS soil moisture, when combined with land surface temperature data, allows to develop fire risk estimates in this region. Interestingly, it was also found that the use of anomalies of both variables improved the detection of high fire risk [Chaparro et al., 2016]. In these study cases, the authors took profit of an operational SMOS-derived soil moisture product, which is available for the Iberian Peninsula at fine scale resolution (1 km), through the Barcelona Expert Centre website [BEC, 2015a, 2015b].

Also, surface temperature data from ERA-Interim models [ECMWF, 2015] were used. In this paper, we are presenting a research that uses the same datasets and takes into account the conclusions derived from those studies (see section “Data and methods”).

The aim of this research is to provide deeper insight in the importance of remotely sensed soil moisture and surface temperature data in relation to wildfires risk in the Iberian Peninsula. Particularly, the objectives of this research are (i) to understand the relation of surface soil moisture and temperature patterns with main fire regimes in the region; (ii) to study surface soil moisture and temperature values prior to fire occurrences in each season, and (iii) to study the applicability of moisture and temperature anomalies for the detection of drought periods when important fire episodes occurred. The research has been conducted for the period 2010-2014 in the Iberian Peninsula, a high fire risk region [San-Miguel-Ayanz, 2013] accounting with the largest burned areas in Europe most years [Joint Research Centre, 2016]. Finally, the study of the effect of soil moisture and temperature anomalies on wildfire episodes (objective iii) was constrained to the northwestern Atlantic region of the Iberian Peninsula (hereafter defined as the northwestern region).

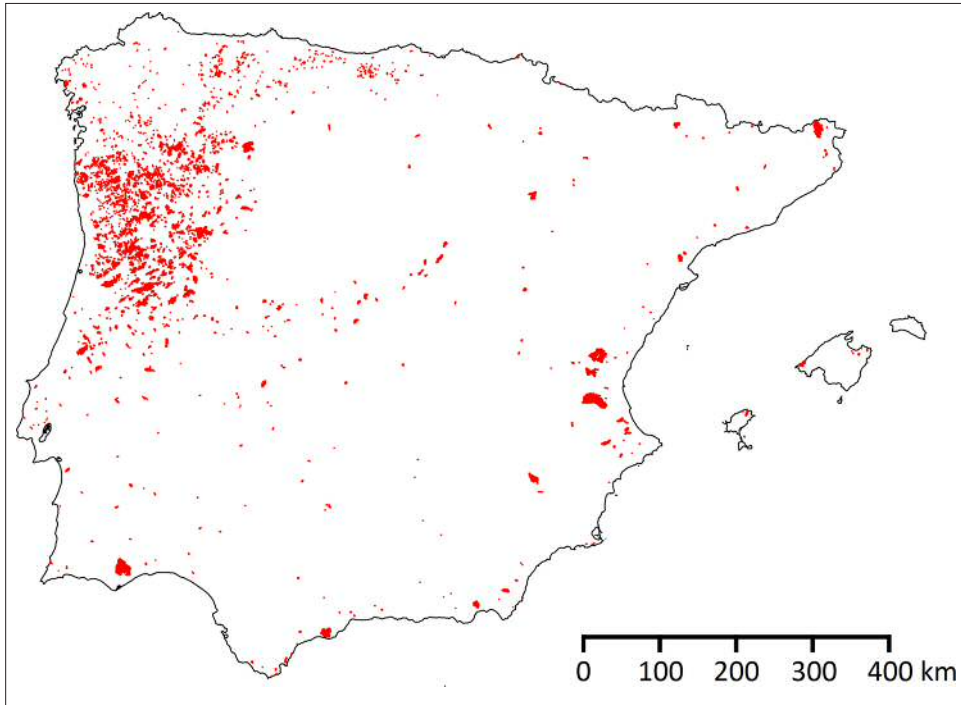
## Data and methods

### *Study area*

The study area includes the Iberian Peninsula and the Balearic Islands (-9.9° W - 4.4° E; 43.9° N - 35.9° N) and encompasses three principal climatic zones. Regions near to the eastern and southern coasts are characterized by hot and dry summers and mild winters, corresponding to a Mediterranean climate. The Iberian central plateau has a continental climate with hot summers and cold winters. The Atlantic regions are characterized by fresher summers, milder winters and generally higher rainfall. Specifically, the northwestern region of the Iberian Peninsula (mainly northern Portugal, Galicia and the Cantabrian coast) has a Euro-Siberian climate where humid conditions prevail. Here, fuel is largely available and numerous fires occur during all the year (mainly in spring and summer), but the high humidity limits their expansion. Human actions (usually agriculture and shepherding) are responsible of most fires in the northwestern peninsular region, resulting on a wide fire season. In contrast, fuel is generally limited in the Mediterranean ecosystems. However, when areas with low fire activity during the preceding years receive high precipitations before summer, the general situation changes and a lot of fuel is finally accumulated. These factors predispose to the burning of several large fires most years during the dry and hot Mediterranean summers [Moreno et al., 2005; Verdú et al., 2012].

### *Fires dataset*

A database containing wildfires larger than 10 ha for the period 2006-2014 has been provided by the European Forest Fires Information System (EFFIS, [European Commission, 2010]). It includes the georeferenced perimeter of each forest fire, the date of fire outbreak and the burned area, among other complementary information. This database has been divided in two groups. The first group includes fires burning between 2006 and 2009, and is used in land cover characterization (see section “Study of anomalies time series and wildfire occurrences in the northwestern Iberian Peninsula”). The second group corresponds to the fires dataset studied in this research and comprises fires burning between 2010 and 2014. In this period, 2,076 fires have been registered in the EFFIS database. They are represented in Figure 1.



**Figure 1 - Wildfires (>10 ha) burned in the Iberian Peninsula during the period 2010-2014 according to the EFFIS database.**

### ***Soil moisture and land surface temperature datasets***

The ESA's Soil Moisture and Ocean Salinity (SMOS) is the first space-borne mission specifically launched to measuring the Earth's surface soil moisture. From its launch in November 2009, SMOS is providing global surface moisture estimates from the soil top 5 cm, with a target accuracy of  $0.04 \text{ m}^3 \cdot \text{m}^{-3}$ , and a spatial resolution of  $\sim 40 \text{ km}$  [Kerr et al., 2010]. This resolution is too coarse for local or regional applications, where at least 1 to 10 km are needed. In the last decade, different downscaling algorithms have been proposed to bridge this gap [Merlin et al., 2008; Piles et al., 2014; Sánchez-Ruiz et al., 2014, Piles et al., 2016]. In this work, the original SMOS product ( $\sim 40 \text{ km}$ ; L2 product) was downscaled to fine-scale (1 km; BEC L4 product) over the Iberian Peninsula using the downscaling method described in Piles et al. [2014]. This method optimally merges SMOS observations with higher spatial resolution MODIS NDVI and LST data into 1 km soil moisture estimates. For this study, the modelled ERA-Interim land surface temperature contained in SMOS L2 product is used as ancillary information to allow estimating cloud-free soil moisture temporal series. This is needed to robustly compute trends and anomalies for the study period. This downscaled moisture data set is available at the Barcelona Expert Centre website [BEC, 2015b]. In this study, only SMOS ascending passes (approximately at 6 a.m., local time) are used, in order to measure the moisture conditions prior to the fire occurrences.

Regarding temperature, the European Centre for Medium-Range Weather Forecasts

provides several models of land surface temperature data [ECMWF, 2015]. Here, a daily reanalysis dataset at 12 a.m. has been used. The initial resolution ( $0.125^\circ$ ) has been adapted to the downscaled moisture data grid using a nearest neighbour interpolation method. Note that this temperature dataset is different from the data used in the downscaling algorithm, considering the time of the measurement and the processing method.

Finally, maps of mean and standard deviation of moisture and temperature have been calculated for the entire study period on the Iberian Peninsula (Fig. 2).

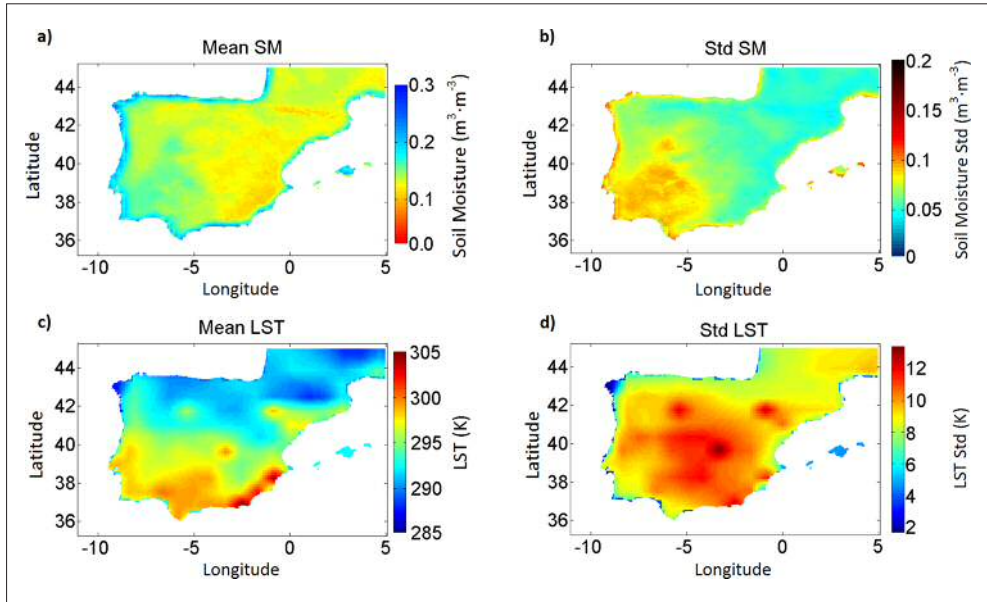


Figure 2 - a) Mean soil moisture (2010-2014), b) Standard deviation of soil moisture (2010-2014), c) Mean land surface temperature (2010-2014), d) Standard deviation of land surface temperature (2010-2014).

### *Soil moisture and land surface temperature anomalies*

Anomaly time series at 9-day and 30-day time scales have been computed from moisture and temperature datasets in order to detect drought periods involving risk of fire. Firstly, monthly means of each variable have been calculated. Secondly, in order to obtain a continuous time series, a linear interpolation has been performed between mean values of each pair of consecutive months. This time series represent the average moisture and temperature conditions. In the third and final step, the difference between moving means and the corresponding average conditions has been calculated from the day of interest to 9 and 30 days backwards.

### *Methods*

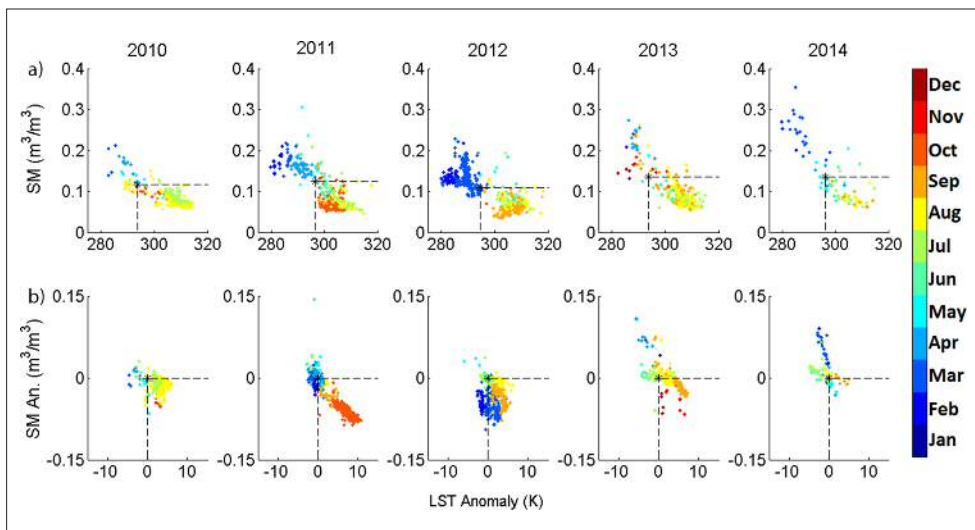
#### **Database construction**

A database containing all the variables related to each fire has been constructed. To that purpose, each fire perimeter has been linked to the moisture and temperature datasets, as

well as to their anomalies. The median values for all pixels within each burned area have been assigned to each fire. Hence, one single datum per burn episode and variable has been registered. These data have been considered only when at least one pair of moisture-temperature values was available from the fire date to three days backwards. In this case, the most recent data has been included in the database. In few occasions, data prior to fire occurrence was unavailable and, consequently, the corresponding fire has been excluded from the study. This has led to a final sample of 2,013 fires (out of the 2,076 fires registered in the EFFIS database).

### Analysis of pre-fire moisture and temperature conditions in the Iberian Peninsula

The study of conditions prior to fire outbreaks in the Iberian Peninsula has been carried out separately by years and months in order to identify the most important fire episodes and when they occurred. For each fire, moisture-temperature data have been coupled to take advantage of the complementarity between both variables, coherently with previous studies [Chaparro et al., 2016]. Also, in order to determine which fires burned in dry and warm soils, reference values approximately defining normal moisture-temperature conditions have been established yearly. These values were calculated as the overall yearly medians of both variables in the study region, and have been used as an approximation to the general conditions of each year. Considering anomalies, zero has been defined as the reference value. Finally, all the information described in this subsection has been plotted in Figure 3 and interpreted in section “Relationship between wildfire occurrences and surface soil moisture and temperatures in the Iberian Peninsula”.



**Figure 3 - a) Mean soil moisture and mean land surface temperature prior to fire occurrences. Black dashed lines represent the yearly median values of temperature and moisture considering the entire Iberian Peninsula. b) Anomalies of soil moisture and anomalies of land surface temperature prior to fire occurrences. In both a) and b) plots, fires are represented per year (columns) and month (colorbar). All the variables were calculated at a 30-day time scale.**

## Study of anomalies time series and wildfire occurrences in the northwestern Iberian Peninsula

Time series of moisture and temperature anomalies have been analysed in relation to important fire episodes which concentrated a high number of fire outbreaks in few weeks. As these episodes were mainly found in the north of Portugal, Galicia and the western Cantabrian coast, the study described in this subsection has been focused on the northwestern Iberian Peninsula.

To specifically delimit the extent of the northwestern region, two GIS layouts have been employed: a map of ecoregions of Spain and a map of phytogeographic zones of Portugal. On the one hand, 53 ecoregions are defined in Spain, and those numbered from 1 to 7 are located in the area of interest. These regions are characterized by a humid, Euro-Siberian climate, and by the typical fire regime from the northwestern region of the Iberian Peninsula (see section “Introduction”). Note that the map of ecoregions of Spain has been previously used with success in fire modelling [Padilla and Vega-García, 2011]. On the other hand, the phytogeographic map of Portugal [Paes do Amaral, 2000; Agência Portuguesa do Ambiente, 2015] divides the country in 24 zones, grouped in 3 broader regions: north, centre and south. The northern region has been included in this study as its climate and its fire regime are similar to that found in northwestern Spain. Finally, Figure 4 shows the study area where the relationship between wildfires and anomalies is studied.

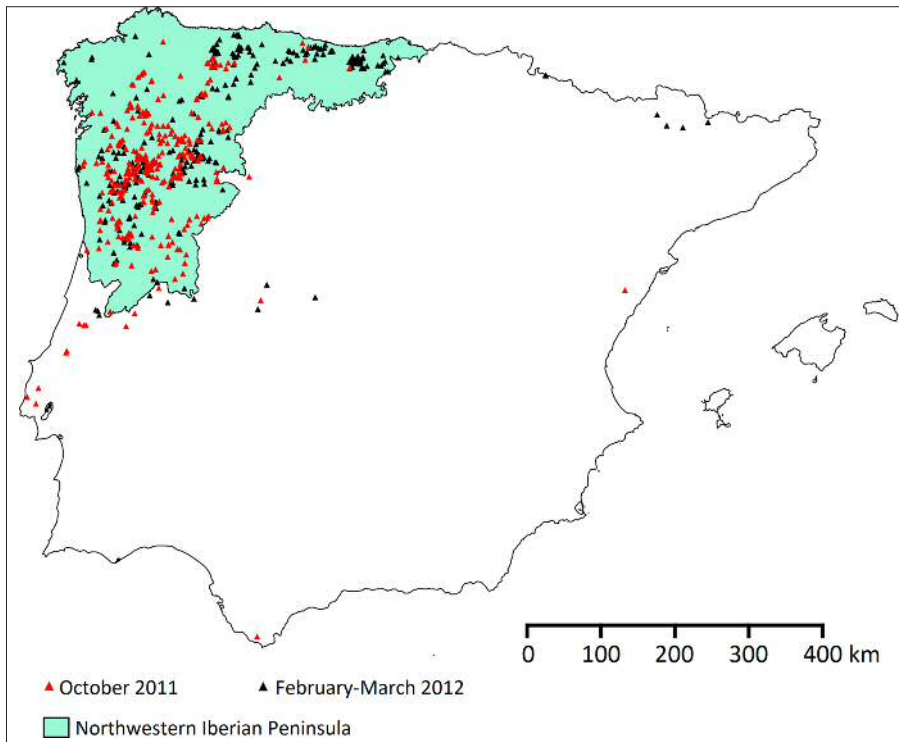


Figure 4 - Fires burned during the two main wildfire episodes (October 2011: red; February-March 2012: black). The green shaded area delimits the northwestern region.

Moisture and temperature anomalies trends were summarized calculating the median anomalies in the region each day, only considering flammable pixels. Hence, pixels located in artificial surfaces and water bodies were excluded using the CORINE Land Cover Map [EEA, 2006]. Also, pixels affected by fire in previous years (2006-2009) and during the study period were not considered.

Finally, the resulting anomalies time series at 9-day and 30-day time scales were compared to the number of fires burning in the region every 9-days and each month. The sample studied in this region was 1,733 fires. This includes 83% of fires of the initial dataset.

## Results

### *Relationship between wildfire occurrences and surface soil moisture and temperatures in the Iberian Peninsula*

Wildfires registered during the study period were irregularly distributed throughout the Iberian Peninsula. While most forest fires burned in Galicia, the Cantabrian coast, and the north of Portugal, few fires occurred in other regions (Fig. 1). However, the largest wildfires burned in the Mediterranean area (Fig. 1), where hot and dry soils prevailed and presented little variability in terms of water content (Fig. 2a, b). In contrast, wetter soils and larger moisture variability were found in the western regions, especially in the southwest (Fig. 2a, b). Soils were colder in the north, while in the southern Iberian Peninsula they reached high temperatures ( $>300$  K; Fig. 2). The largest variability of land surface temperatures was found in the central Iberian Peninsula (Fig. 2d).

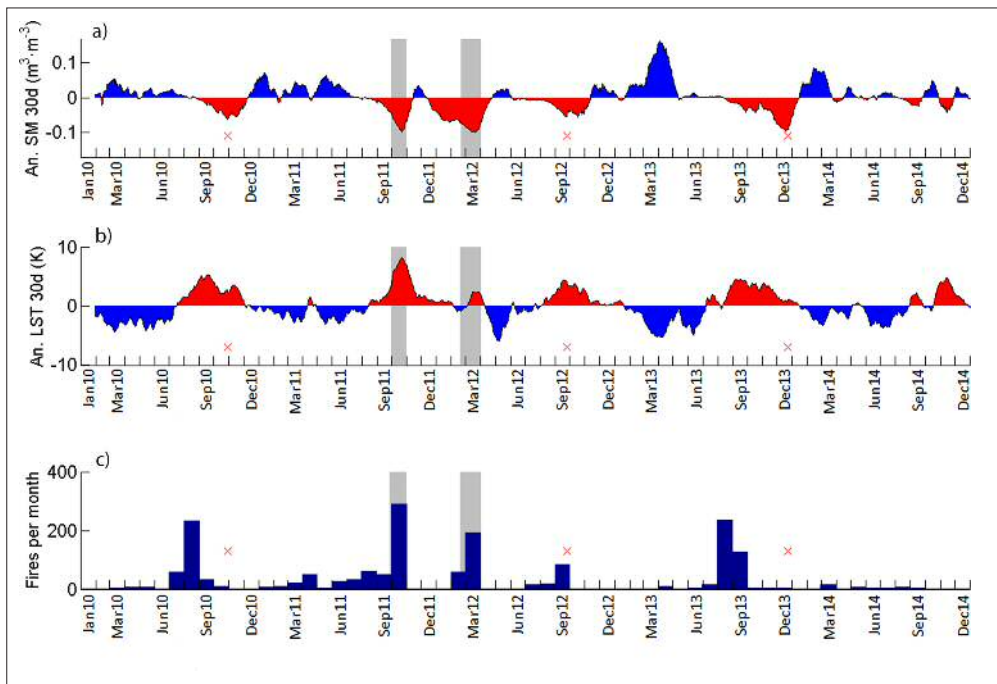
The studied fires were classified by year and by month, and were plotted in Figure 3a as a function of moisture and temperature, and in Figure 3b as a function of the anomalies of both variables. Pre-fire moisture and temperature were also compared to yearly average conditions in the Iberian Peninsula, showing that the warmest and driest years in the study region (2011 and 2012, respectively) coincided with the years with more fire outbreaks (Fig. 3a). Particularly, the highest percentage of forest fires corresponded to 2011 (29.7%), followed by 2012 (23.9%), 2013 (23.1%), 2010 (18.6%) and 2014 (4.7%). Most wildfires burned when temperature was higher and moisture was lower than the overall yearly averages (i.e. reference values plotted as dashed lines in Fig. 3a), which hereafter will be simply defined as fires occurring under dry and hot soils (Fig. 3a). In particular, 75% of fires burned in these dry-hot conditions considering 30-day means (Fig. 3a; 73% for 9-day, not shown). Regarding moisture and temperature anomalies, soils drier and hotter than the average preceded the 68.7% of fire outbreaks (30-day anomalies, Fig. 3b; 76.6% for 9-day, not shown). These percentages varied depending on years and seasons. During 2010, 2011 and 2013, from 77% to 89% of ignitions happened in dry and hot soils. This percentage was lower in 2014 (60% to 65%). In 2012, 267 wildfires (54% of the fires studied that year) occurred in February and March, when soils were wet and cold in absolute terms (Fig. 3a). However, the prone-to-fire situation leading to this remarkable episode was detected by the 30-day moisture anomalies, as 99% of these wildfires occurred in drier than average conditions (Fig. 3b). This percentage was lower for the 30-day temperature anomalies (66%). Considering other fire periods occurring in cold and wet soils (e.g. February-April 2011 and February-March 2014), they did not burn in anomalous conditions. In these particular cases only 89 and 24 fires were registered, respectively (Fig. 3). Finally, an exceptional situation occurred during October 2011, when 304 fires burned. During the month prior to fires, soil



water content reached  $0.09 \text{ m}^3 \cdot \text{m}^{-3}$  below the average, and temperatures rose up to 10.9 K above the mean conditions (Fig. 3b). This situation got worse in the 9 days before fires ( $-0.12 \text{ m}^3 \cdot \text{m}^{-3}$  and  $+14.3 \text{ K}$ ).

### *Linking anomalies and fire occurrences in the northwestern Iberian Peninsula*

A high proportion of the registered fires (27%) happened during the two exceptional episodes of October 2011 and February-March 2012, and burned mainly in the northwestern Iberian Peninsula (Fig. 4). The anomalous conditions preceding these wildfire episodes were studied, and the relationship between droughts and fire occurrences in the northwest was analysed. Figure 5 (a and b) shows the average soil moisture and temperature anomalies in the region (30-day time scale). Their values can be compared with the number of wildfires burning each month (see Fig. 5c). Considering the soil moisture anomalies shown in Figure 5a, five droughts occurred in the region during the study period: (i) August-November 2010, (ii) August-November 2011, (iii) December 2011-April 2012, (iv) August-November 2012, and (v) August-December 2013. Generally, positive temperature anomalies coincided in time with these periods (Fig. 5b). Results using 9-day time scale anomalies were coherent with that from 30-day timescale, but showed more irregular patterns (results not shown).



**Figure 5 - Dry and wet periods compared to fire outbreaks in the northwestern Iberian Peninsula during the period 2010-2014. a) Median anomalies of soil moisture at 30-day time scale; (b) median anomalies of land surface temperature at 30-day time scale; and (c) number of fires grouped per month. Red crosses represent periods when dry and warm soils did not lead to the occurrence of important fire episodes.**

The exceptional wildfire activities registered in October 2011 and February-March 2012 (highlighted in Fig. 5) coincided with the droughts detected from August to November 2011, and from December 2011 to April 2012. In October 2011, abnormally dry soils and high temperature conditions started in July and August, respectively, and lasted until November. Driest soils (up to  $-0.09 \text{ m}^3 \cdot \text{m}^{-3}$ ) and highest surface temperature anomalies (up to  $+8 \text{ K}$ ) occurred in October, when the most extreme values of both variables matched in time (Fig. 5). Also, forest fire outbreaks of February and March 2012 burned in extremely dry conditions, as soil moisture anomalies reached a minimum of  $-0.10 \text{ m}^3 \cdot \text{m}^{-3}$  in March 2012 (Fig. 5a), coinciding with the highest values of temperature anomalies ( $+1.6 \text{ K}$ ). While soils were continuously dry for more than 3 months before this episode, the duration of high temperatures was only limited to the month of March (Fig. 5b).

Not all the drought situations led to exceptional wildfire activity. From August to November 2010, the number of fire occurrences was important only in August and September, when summer conditions facilitated the ignition of wildfires (see Fig. 3a). A similar situation was found from August to December 2013. In both cases, minimum moisture conditions ( $-0.06 \text{ m}^3 \cdot \text{m}^{-3}$  in October 2010, and  $-0.09 \text{ m}^3 \cdot \text{m}^{-3}$  in December 2013) occurred later than maximum anomalies of temperature (Fig. 5a, b). Finally, in September 2012, the driest and warmest conditions occurred simultaneously. However, the drought was shorter and milder if compared to the periods August-November 2011 and December 2011-April 2012 (Fig. 5a) and the number of fires was also smaller (109 wildfires burned in September 2012, while 304 and 267 occurred during the two main wildfire episodes).

## Discussion

### *Main fire regimes in the Iberian Peninsula were linked to moisture and temperature patterns*

The distribution and extent of wildfires in the Iberian Peninsula were coherent with the contrasting climate-fire patterns in the region (i.e. northwestern and Mediterranean regimes). On the one hand, high moisture facilitates the accumulation of a lot of fuel in the forested landscapes of the northwest. However, this fuel is humid and its low flammability limits the spread of wildfires. On the other hand, generally, a minor fuel accumulation due to more reduced water availability limits the number of ignitions in the Mediterranean. Still, in particular situations when fuel finally accumulates, the dry summer conditions can lead to the occurrence of large forest fires [Verdú et al., 2012]. Besides the comparison between these two Iberian regions, note that the southwestern Iberian Peninsula was the most humid area in terms of average soil moisture (Fig. 2a). This shows that fuel accumulation is possibly more dependent on precipitation (higher in the northwest [Ninyerola et al., 2003]). Actually, soil moisture is influenced by different factors and precipitation is not the only important variable conditioning moisture, as shown in recent studies [Polcher et al., 2016]. Also, the high variability of moisture in the southwest (Fig. 2b) and the high temperatures in this area (Fig. 2c) suggest that dry and hot soils occur in some periods and might restrict the availability of combustible.

### *Dry and warm soils favoured the occurrence of wildfires*

High soil surface temperatures in 2011 reflected the prevailing high air temperatures in the Iberian Peninsula during that year. In 2012, dry soils were related to the extremely low

precipitations in the study area (Fig. 3; [AEMET, 2011 and 2012]). Both years registered the highest fire activity in the study period. In contrast, the number of fire outbreaks in 2014 was unexpectedly low regarding the general conditions. Hence, an overall yearly value for each variable was not descriptive enough of the real situation in 2014, and a more detailed analysis is needed in this year. Generally, in 2014, winter months were very hot and rainy, while summer was not markedly abnormal with respect to climatic air temperatures and precipitations [AEMET, 2014], which probably explains the low number of fire occurrences during that year.

The studied variables strongly conditioned fire occurrences when analysed at 9-day and 30-day time scales. Most fires from June to October burned in dry and warm soils, usually at  $LST > 295 \text{ K}$  and  $SM < 0.11 \text{ m}^3 \cdot \text{m}^{-3}$  (Fig. 3). The complementarity between high temperatures and low moisture created prone-to-fire conditions during summer and early-autumn, coherently with similar results reported in [Chaparro et al., 2016]. Still, numerous fires occurred in the northwestern Peninsula during winter and spring seasons. Despite of the cold and wet conditions of these months, the analysis of moisture and temperature trends permitted the detection of the anomalous conditions which led to the extraordinary fire episode of February-March 2012 and of October 2011 (Fig. 3).

### ***Surface moisture-temperature anomalies were linked to drought and fire risk periods in the northwestern Iberian Peninsula***

The high number of fire outbreaks of October 2011 and February-March 2012 coincided in time with the driest and warmest soils during the corresponding droughts (Fig. 5). Interestingly, these two periods of high fire activity occurred under synoptic meteorological anomalous conditions, when the anticyclonic activity in the region caused abnormally high air temperatures and low air humidity [Amraoui et al., 2014]. This reports the capacity of the computed anomalies to detect drought situations increasing the risk of forest fires (at least out of summer conditions).

Not all the drought situations led to a high number of fire outbreaks; as explained in section “Results”, it also depends on the drought duration and intensity. Additionally, it is important to outline that the coincidence in time and space of low soil moisture and high temperatures was important to determine the number of fire occurrences.

Finally, considering the studied summers, anomalies of both variables were generally close to 0 (Fig. 5). High temperatures and dry soils are frequent in the Iberian Peninsula during summer, and absolute values are better indicators of fire risk (and probably also of drought) during this season (see section “Dry and warm soils favoured the occurrence of wildfires”). Both moisture and temperature anomalies were evaluated at 9-day and 30-day time scales. The 9-day approach showed increased effect of anomalies preceding wildfires if compared to the previous 30 days. However, clearer patterns for time series of both variables were found at 30-day timescale (Fig. 5). Hence, 30-day anomalies were considered to be more adequate for detecting drought episodes involving risk of forest fires.

### ***Applicability of remotely sensed soil moisture and surface temperature data in forest fire risk assessment***

The expected increase on wildfire frequency mainly in the northern Iberian Peninsula [Scholze et al., 2006], and the observed expansion of the fire-weather season in the

Mediterranean areas [Jolly et al., 2015] stress the need of continuously evolving in fire risk detection techniques and models in the Iberian Peninsula. In that sense, new space-borne observations of soil moisture offer the opportunity of an accurate monitoring of this key variable. In addition, advanced modelling methods for surface temperature permit the study of this variable at different time and spatial scales.

In this study, remotely sensed soil moisture and modelled land surface temperature data have been found to be important variables in drought detection and fire risk assessment in the Iberian Peninsula. The complementarity between these variables both in absolute and relative terms, and the importance of moisture-temperature anomalies in fire risk detection out of the summer season, open a path forward in the applicability of remotely sensed soil moisture and surface temperature data in early warning systems preventing forest fires.

In addition, the analysis of fire risk based on soil moisture-temperature information could be enhanced with the application of remotely sensed land surface temperature from geostationary satellites, such as Meteosat Second Generation, to improve the spatio-temporal resolution of the estimates [Piles et al., 2016].

Finally, future work should be addressed to the development of fire risk models integrating soil moisture-temperature data within fire risk tools including other important weather-related variables (e.g. wind), as well as vegetation and orography information.

## Conclusions

The relationship of forest fires with soil moisture and temperature patterns was studied in the Iberian Peninsula and the Balearic Islands between 2010 and 2014. The main fire regimes and wildfire episodes found in the region were associated to moisture-temperature conditions computed at 9 and 30-day time scales.

Differences in fire activity and behaviour between the northwest and the Mediterranean areas, which correspond to different fire regimes, were linked to the average 5-year moisture and temperature conditions in both regions. As expected, dry and warm soils limited the fuel availability in the Mediterranean, but at the same time facilitated the flammability of vegetation in summer, when few large forest fires burned (mean area = 2872 ha). Contrarily, wetter and colder soils in the northwest were partially linked to the presence of large amounts of wet combustibles, which are related to the occurrence of numerous smaller wildfires (mean area = 608 ha). Most forest fires burned in the Iberian Peninsula in drier and hotter soils than the yearly averaged conditions found in the region during the study period. Specifically, low moisture and high temperatures measured in absolute terms preceded the ignition of most wildfires during summer and early autumn. Also, moisture and temperature anomalies, especially those measured at 30-day time scale, were useful to detect adverse conditions leading to important fire episodes in October 2011 and in February and March 2012. Both fires events accounted with almost 30% of wildfires larger than 10 ha registered during the study period. These forest fires burned principally in the northwest.

Focusing in the northwestern region, five drought periods were detected in the northwestern Iberian Peninsula using 30-day moisture and temperature anomalies. The longest and more intense droughts coincided with abnormally anticyclonic activity at synoptic scales, reporting the capacity of the computed anomalies to detect drought periods involving high fire risk. These drought episodes coincided with the main fire periods studied (October 2011 and February-March 2012), and reached extreme dry soil conditions (until  $-0.09 \text{ m}^3 \cdot \text{m}^{-3}$ )

and, in the case of October 2011, temperatures highly above mean (+8 K). The contrast in the number of fire occurrences among the five droughts studied was dependent on the intensity and duration of droughts, and on the association between extreme moisture and temperature values.

Results from this study show that SMOS-derived soil moisture and modelled surface temperature datasets provide complementary information for the detection of drought situations leading to high risk of extreme fire events, and that both their absolute values and their trends are needed to cover forest fires occurring in all seasons. This research is a contribution to the improvement of fire risk assessment techniques in the Iberian Peninsula, and can help facing the increase of wildfire activity in the region caused by climate change.

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