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Trends in LST over the peninsular Spain as derived from the AVHRR imagery data

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Abstract

This study analyzes the spatio-temporal variability and trends of land surface temperature (LST) over peninsular Spain, considering all the available historical satellite imagery data from the NOAA-AVHRR product from July 1981 to June 2015 and explores whether changes in LST are related to the observed changes in air temperature, solar radiation and land cover. We found that LST showed a significant increase between 1982 and 2014, with an average increase on the order of $0.71\text{ }^{\circ}\text{C decade}^{-1}$, being stronger during summertime ($1.53\text{ }^{\circ}\text{C decade}^{-1}$). The results also indicate a strong spatial coherence between LST and NDVI changes. The areas that experienced an increase in the LST were spatially consistent with those areas with no changes or even a dominant decrease in vegetation coverage. In addition, the strong increase of LST is coherent with observations of the recent radiative forcing affecting Spain, particularly during summertime. The confidence of the obtained LST trends during summer is also reinforced by the spatial differences recorded in trends, in addition to the differences found between land cover types. Specifically, the magnitude of this increase was much higher in the dryland non-permanent agricultural areas, which are usually harvested during summer, when soil is dominantly nude. In contrast, in well-developed forests, the magnitude of LST was much lower. Our results on the observed LST trends and their spatial patterns can contribute to better understanding of the recent eco-hydrological processes in peninsular Spain.

Keywords: Land surface temperature, NDVI, remote sensing, trends, global warming, aridity.

1. Introduction

A wide range of studies emphasized the role of recent global change processes on both natural and human environments (Root et al., 2003; IPCC, 2013). A key feature of these global changes is the unprecedented increase of air temperature over the last five decades, in comparison to the past 500 years (Luterbacher et al., 2004). More specifically, temperature rise has noticeably been reinforced over the past five decades, showing a generally global increase higher than 1°C on average (Easterling et al., 1997; Jones et al., 1999, 2012; Jones and Moberg, 2003). In Europe, numerous studies showed a significant increase in mean air temperature as well as the frequency and intensity of heatwaves during the past five decades (Barriopedro et al., 2011; Seneviratne et al., 2014). Over Spain, an increase in air temperature has also been recorded at different spatial and temporal scales (e.g. Brunet et al., 2007; del Río et al., 2012; El Kenawy et al., 2011, 2012; Sánchez-Lorenzo et al., 2012; Gonzalez-Hidalgo et al., 2015). This temperature rise is combined with complex land cover transformations (Lasanta and Vicente-Serrano, 2012).

Land cover changes across Spain are widely associated with land marginalization in rural areas, which favored a process of natural revegetation (García-Ruiz et al., 1996; Lasanta et al., 2005; Hill et al., 2008; García-Ruiz and Lana-Renault, 2011). On the contrary, while land intensification has been observed over some regions in Spain, mainly due to transformation of drylands to irrigated areas (Lasanta and Vicente-Serrano, 2012, other regions have been affected by land degradation processes (Del Barrio et al., 2010; Vicente-Serrano et al., 2012). As such, both climate change processes and land transformations have combined together to affect many surface parameters over Spain, including land-atmosphere water fluxes, energy balances, etc. Among these parameters, land surface temperature (hereafter LST) is an essential variable, which is a direct driving force of turbulent heat fluxes, long-wave radiation exchanges (Maurer et al., 2002; Nishida et al., 2003) and actual evapotranspiration (e.g.

Nishida et al., 2003; Fisher et al., 2008; Kustas and Anderson, 2009; Anderson et al., 2012; Li et al., 2013; Nguyen et al., 2015). Thus, LST is a key variable in formulating energy and water budgets at different spatial scales, varying from local to global (Anderson et al., 2008; Zhang et al., 2008; Kustas and Anderson, 2009; Karnieli et al., 2010; Li et al., 2013). Moreover, changes in LST can give insights on different processes, such as vegetation conditions (Weng, 2009; Hereher, 2016), drought severity (Kogan, 2001; Karnieli et al. 2010), land degradation (Garcia et al., 2008) and urban sprawl (Voogt and Oke, 2003; Tam et al., 2010).

Numerous studies provided evidence on enhanced drought severity and dryness in Spain, as a function of precipitation decrease as well as increased atmospheric evaporative demand (AED) (Vicente-Serrano et al., 2014a). Recent changes in the AED are not only driven by air temperature increase, but they are linked to the strong decrease of relative humidity over the last five decades as well (Vicente-Serrano et al., 2014b). Also, natural vegetation growth and reforestation in mountain humid regions may increase water demand through vegetation via transpiration processes (Begueria et al., 2003; García-Ruiz and Lana-Renault, 2011), which would contribute to explaining the decrease of streamflow across large areas of Spain (Lorenzo-Lacruz et al., 2012a; López-Moreno et al., 2012).

There is a growing interest in assessing the evolution of the global solar radiation (hereafter GR) into the Earth surface, given the observed changes during the past decades. Since 1980, different studies have pointed out a general increase in the GR across large areas of the world (Wild et al., 2005), including the Iberian Peninsula (Sánchez-Lorenzo et al., 2013). Increased GR could therefore noticeably affect land-atmosphere fluxes and determine changes in water availability and aridity conditions.

All these processes suggest complex environmental transformations in Spain, as a consequence of the interaction between climate changes, human land transformations and

eco-hydrological processes. Thus, the complexity of these interactions may explain the existence of strong uncertainties in relation to the impacts of global change processes. The assessment of LST variability and trends may help advance our knowledge of some paradoxical and contradictory processes reported in earlier works across Spain, such as the coincidence of reinforced climate aridity (Hoerling et al., 2012; Vicente-Serrano et al., 2014a), the strong growth of vegetation activity and coverage (Vicente-Serrano et al., 2004; Hill et al., 2008; García-Ruiz and Lana-Renault, 2011) and the secondary tree growth decay processes (Carnicer et al., 2011; Camarero et al., 2015a; Guada et al., 2016).

In Spain, different studies have analyzed long-term variability and trends of surface parameters estimated from remote sensing data. Most of these studies have focused on visible and near infrared image to estimate indices of vegetation activity (e.g. Hill et al., 2008; Del Barrio et al., 2010). Nonetheless, although several studies have focused on the development of algorithms for an accurate estimation of LST from NOAA-AVHRR data (e.g. Sobrino et al., 1991; Coll et al., 1994), few works employed these well-calibrated and homogeneous remote sensing datasets for environmental applications across Spain (Ruescas et al., 2010; Julien et al., 2011). Among these space-based data, LST can provide excellent information to understand radiative and water flux processes. Unfortunately, a comprehensive assessment of the potential of the available time series of thermal infrared data over the past three decades is still lacking over Spain.

The main objectives of this study are twofold. First, we analyze the spatio-temporal variability and trends of LST over peninsular Spain, considering all available historical satellite imagery data from the NOAA-AVHRR product for the period July 1981-June 2015. Second, we explore the possible drivers of this variability, with a particular focus on the links between change in LST and those of air temperature, solar radiation and land cover.

2. Datasets

2.1. Land Surface Temperature (LST)

LST can be obtained using a wide range of infrared radiometric information provided by different sensors on board of satellite platforms; some of them record these data from the early 1980s. LST from the NOAA (National Oceanic and Atmospheric Administration)-AVHRR (Advanced Very High Resolution Radiometer) data has been widely employed in various environmental studies over the past decades. Indeed, there is a high uncertainty in estimating LST over continental areas, which can be originated from the high diversity of land cover types, which are characterized by different values of thermal emissivity (Sobrino et al., 2001). Also, changes in land cover may affect thermal properties of the surface. Contrarily, this information is less uncertain over water surfaces, where estimating surface temperature is less problematic, allowing for obtaining long time-series of sea surface temperature (Reynolds et al., 2002).

Albeit with the notion that the NOAA-AVHRR thermal bands have been widely used, only few studies have employed the available long-time series of LST. This lack of studies is mainly attributed to the problems associated with the correction of LST estimations for platform orbital drift (Prince, 1991). In this study, we employed LST data at a 1.1 km spatial resolution. Our historical daily NOAA-AVHRR dataset comprises 12,418 afternoon images spanning the period from July 1981 to June 2015 and covering the entire Iberian Peninsula. The images used in this study were acquired from different sources, including: the Dundee Satellite Reception Center (images from 1981 to 1986), the European Spatial Agency (images from 1986 to 1997), and the Advanced High Resolution Picture Transmission (AHRPT/HRPT) antennae (images from 1998 onwards), located at the *Centro de Recepción, Proceso, Archivo y Distribución de Imágenes de Observación de la Tierra* (CREPAD) and

coordinated by the Spanish National Institute of Aerospace Technology (INTA) in its Canaries Space Centre (Maspalomas, Gran Canaria).

To maintain the consistency among images from different sources and with different formats, we designed and implemented automated scripts in IDL language. Herein, it is noteworthy emphasized that we used the complete range (1 to 5) of available AVHRR bands, besides two thermal bands (4 and 5). This procedure was particularly motivated by the fact that calculating LST necessitates all information from the visible, near-infrared and medium infrared spectral regions to properly estimate surface emissivity and obtain robust cloud coverage masks. Overall, we first applied a geometric correction to the digital numbers of the NOAA-AVHRR images using the algorithm developed by Baena-Calatrava (2002), which is based on satellite parameters followed by geometric corrections. This second geometric correction used field observations of land cover patterns of a set of 97 Ground Control Points (GCP) (Ho and Asem, 1986), which are located in coastal accident (e.g. capes) as well as in continental sites (e.g. reservoirs). The corrected images were then re-projected to the European-ED50-UTM zone 30°N for a geographical domain bounded between 34°22'N and 44°12'N and 11°7'W and 4°16'E.

Second, we calibrated the different satellites (Price, 1991). Initially, we applied a linear correction to obtain the radiance recorded by the satellite (L_a) from the digital number (DNs), using the coefficients embedded in the images (G and I) for bands 4 and 5. These coefficients are different for each line of the image, where

$$L_a = G \times DN + I \quad (1)$$

The radiances were corrected non-linearly for the satellites N-7, N-9, N-11 and N-14, following:

$$L = AL_a + BL_a^2 + C \quad (2)$$

where A, B and C are the coefficients defined by Walton et al. (1998) and retrieved for the NOAA-7 to NOAA-14 satellites and from the NOAA user guide for the NOAA-16, NOAA-18 and NOAA-19 (<http://www.ncdc.noaa.gov/oa/pod-guide/ncdc/docs/klm/html/d/app-d2.htm>; accessed on 1st February 2017).

Brightness temperatures (T_B) were obtained from radiances according to the Planck equation, formulated as:

$$T_B = \frac{c_2 v}{\ln\left(1 + \frac{c_1 v^3}{L}\right)} \quad (3)$$

where $c_1 = 1.19104 \cdot 10^{-5} \text{ mWm}^{-2}\text{sr}^{-1}(\text{cm}^{-1})^{-4}$ and $c_2 = 1.43877 \text{ K}(\text{cm}^{-1})^{-1}$. The values of v vary from one satellite to another and can be found in the NOAA satellite specifications (<http://www.ncdc.noaa.gov/oa/pod-guide/ncdc/docs/podug/html/c1/sec1-4.htm>; accessed on 1st February 2017).

Once brightness temperatures were obtained, we removed cloudy pixels. For this purpose, we used the robust cloud detection algorithm detailed by Azorin-Molina et al. (2013). To limit the possible influence of cloud shadows, we also removed three pixels around each identified cloudy pixel. We also removed those pixels with observation angles higher than 50° , to avoid any geometric and radiometric problems related to the view angle of the satellites.

Red and near-infrared bands were calibrated using revised calibration coefficients considering the orbit degradation for each satellite (Rao and Chen, 1995, 1999; <http://www.ncdc.noaa.gov/oa/pod-guide/ncdc/docs/intro.htm>; accessed on 1st February 2017).

Radiances from channel 1 and 2 were transformed to top-of-the atmosphere reflectance and cross-calibrated to the NOAA-9 sensor to correct the different spectral responses of the sensors (Trishchenko et al., 2002; 2009). Finally, the reflectance was topographically corrected by means of a non-Lambertian model using a digital elevation model at a resolution of 1.1 km (Riaño et al., 2003).

To obtain LST, we applied a split-window algorithm developed by Sobrino and Raissouni (2000) and widely tested by the atmospheric conditions of the Iberian Peninsula, following:

$$LST = T_4 + c_1(T_4 - T_5) + c_2(T_4 + T_5)^2 + c_0 + (c_3 + c_4 W)(1 - \varepsilon) + (c_5 + c_6 W) \Delta \varepsilon \quad (4)$$

where W is the water vapor content in each pixel of the image, calculated according to the algorithm of Sobrino et al. (2002), which is valid for the latitudes of the Iberian Peninsula. W was computed, as:

$$W = 0.259 - 14.253(\cos \theta \ln R) - 11.649 (\cos \theta \ln R)^2 \quad (5)$$

where R is calculated for free-of-clouds pixels, whose view angle was lower than 50° , according to:

$$R = \frac{\sum_{k=1}^N (T_{4,k} - T_{4,0})(T_{5,k} - T_{5,0})}{\sum_{k=1}^N (T_{4,k} - T_{4,0})^2} \quad (6)$$

where $T_{4,k}$ is the value of the pixel k in the band 4; $T_{4,0}$ is the average of all the available pixels in the band 4. $T_{5,k}$ is the value of the pixel k in the band 5; $T_{5,0}$ is the average of all pixels in the band 5. The emissivity ε and $\Delta \varepsilon$ were obtained according to the method developed by Sobrino et al. (2008) using thresholds of the NDVI values from the red and near-infrared bands. The coefficients c_0 to c_6 for each satellite were obtained following Lahraoua et al. (2013).

Given the different sun angles and radiation received by the surface, LST may vary as a function of the viewing angle (Wan and Dozier, 1996) as well as the time at which the images are taken (Price, 1991). Julien and Sobrino (2012) illustrated that orbit drift is an important source of noise in LST time-series. As developing a physical approach to correct these effects is a challenging task, we applied a statistical approach similar to that followed by Julien and Sobrino (2012). The aim was to limit the effects of the different solar zenith and observation angles from each daily LST image. Given the strong seasonality found in solar effects, we split the available daily time series in semi-monthly series (all the images between 1st January

and 15th January, between 16th January and 31th January and so on). Following this procedure, we produced 24 series of LST for the period 1981-2015. For each series and pixel, we removed the effect of the zenith and observation angles by means of a multiple regression model, according to:

$$\text{LST} = a + b * a_z + c * a_o \quad (7)$$

In which a , b and c are the regression coefficients and a_z and a_o are the solar zenith and observation angles, respectively. Based on these coefficients and after removing the residuals that were expressed as observed minus predicted LST, we calculated the free-effect LST (LST_c), according to:

$$\text{LST}_c = m + (\text{LST} - (a + a_z * b + a_o * c)) \quad (8)$$

where m is the average LST calculated for the semi-monthly time series.

Figure 1 illustrates the spatial distribution of the Pearson's r correlations between LST and solar and observation angles for the series of the first half of July and the percentage of the variance explained by the two angles, as suggested by the multiple regression model. As noted, there is a negative correlation between LST and solar angle, but with remarkable spatial differences, mostly driven by land cover distribution. On the contrary, the correlation between LST and observation angle is very weak (close to zero). Figure 1 also suggests that, in some areas of Spain, almost 30% of daily variability of LST during the first half of July can be explained by solar and observation angles.

Figure 1: Spatial distribution of Pearson's r correlations between the daily LST and solar (upper left) and observation (upper right) angles and the percentage of the variance (bottom) explained by the multivariate regression model. All calculations were made for the series of the first half of July over the period from 1981 to 2015.

Figure 2 summarizes the coefficient of determination (r^2) of the regression models and their corresponding p -value, obtained for each semi-monthly period. The more pronounced influence of solar and observation angles on LST is observed during summer months, with almost 15-20% of LST variance being explained by these angles. In the same context, it is found that most of the regression models are statistically significant (p -value < 0.05) during summertime, which demonstrates that both observation and solar angles impact LST variability and therefore their influence should be limited.

Figure 2: Box-plots showing the r^2 of the regression models obtained for each semi-monthly period and their corresponding p-values.

Figure 3 shows the average semi-monthly (see below) LST for the whole peninsular Spain from 1981 to 2015, with the black line representing the calibrated LST, while the red line shows the corrected LST (by means of solar and observation angles) for the different satellites. It can be noted that changes in the correction procedure affect summer months. Similarly, a quick inspection of the fitted linear regression lines for the period of the data of each satellite and that of the whole period reveals that our correction procedure was skillful in reducing the inter-annual variability caused by combining data from different satellites, particularly those of the NOAA 11 and NOAA 14. Besides, this procedure reduces the magnitude of the positive LST trend observed over the whole period. As illustrated in Figure

3, while LST data from the NOAA 16, 18 and 19 exhibit low correction following our regression methodology, larger corrections are made for the NOAA 9, 11 and 14, particularly at the end of their lives.

Figure 3: Temporal evolution of the semi-monthly LST between 1981 and 2015. Black (red) curve indicates the non-corrected (corrected) LST. The fitted linear regression lines for the data period calibrated by each satellite and the whole period are also plotted

After applying the correction procedure, daily LST series were composited in semi-monthly periods (two per each month: from 1st day of the month to the 15th, and from 16th to the end of the month) using the maximum temperature recorded in the period, with the aim of reducing uncertainty associated with any remaining residuals either from atmospheric effects or cloud cover.

To fill gaps in the series, which can be originated from clouds, large observation angles and geometric distortions, we applied a linear regression model, considering LST values before and after each gap as predictors. This procedure was applied iteratively to account for all gaps existing in the series. Then, in order to reduce residual noise presented in the series, we filtered data of each series following Quarmby et al. (1993). According to this approach, only low LST values are filtered, given that high values are less affected by atmospheric contamination and residual noise. Overall, the series were filtered, as:

$$LST = \text{Max}\{LST_{(n)}, (LST_{(n-1)} + LST_{(n+1)})/2\} \quad (9)$$

Finally, we calculated the monthly, seasonal and annual averages of LST series using the semi-monthly series. Herein, seasons are defined as: winter (DJF), spring (MAM), summer (JJA), and autumn (SON).

2.2. Maximum air temperature

To investigate the relationship between the spatio-temporal variability of LST and air temperature, we used the available information on maximum air temperature (Tmax) in Spain. For this purpose, we created a gridded 1.1 km monthly Tmax dataset for the peninsular Spain using the Monthly Temperature Data for Spain (MOTEDAS) dataset (Gonzalez-Hidalgo et al., 2015). MOTEDAS was developed using the most complete register (till 2015) of raw time series of air temperature, provided by the Spanish National Meteorological Agency (AEMET), for Spain. This product incorporates the most complete, quality-controlled and homogenized air temperature series for Spain. In this study, our decision was made to focus on Tmax because it is comparable to LST, given the time of acquisition (i.e. afternoon passes) of the NOAA-AVHRR imagery data. A detailed description of the generation and validation of our Tmax gridded dataset is outlined in Khorchani et al., (2018).

2.3. Normalized Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) dataset at a spatial resolution of 1.1 km was used to assess the relationship between changes in LST and those of vegetation coverage. We computed the NDVI for the study domain using the same NOAA-AVHRR dataset and keeping the same spatial and temporal coverage of LST dataset. More details on the procedure we followed to create the NDVI dataset and its performance against different available global NDVI datasets are given in Martin-Hernandez et al. (2017).

2.4. Solar radiation (GR) and sunshine duration (SUN) data

GR is the major component of surface energy balance and a main driver of a wide variety of surface processes, such as evapotranspiration and associated hydrological components (Wild, 2009). Thus, and in order to explore the effect of GR on the evolution of LST, we obtained the complete GR dataset for Spain, provided by the Spanish National Meteorological Agency (AEMET). This dataset consists of daily records (W.m^{-2}) measured for around 70 meteorological stations. Nevertheless, this dataset comprises data gaps in almost all series, with only 9 stations being recuperated for a common period (Supplementary Figure 1, Supplementary Table 1). To overcome this problem, we used a gridded dataset of sunshine duration (SUN) data for the same period over Spain. Several studies have underlined the SUN-GR relationships and SUN records have been used widely to estimate GR data (Angstrom, 1924; Hay, 1979; Bakirci, 2009; Das et al., 2015; Li et al., 2011). Over Spain, Azorín-Molina et al. (2015) found strong agreement between the temporal variability of SUN and GR over the last three decades. For this reason, several studies used SUN data to reconstruct GR for longer periods (e.g. Sanchez-Romero et al., 2016; Anton et al., 2017). Recalling that estimation of GR data is beyond the scope of this study, we merely employed the available SUN grids to be compared with LST. We believe that SUN data can adequately reflect the effect of the radiative forcing on the evolution of LST. Herein, we used gridded SUN data, with a grid interval equivalent to LST data, for more than 50 quality-controlled, homogenized and spatially well-distributed weekly SUN series across peninsular Spain. Details on SUN dataset development and its validation can be found in Vicente-Serrano et al. (2017). As illustrated in Figure 4, this gridded dataset shows strong temporal agreement with the available GR data for Spain. Correlations are generally higher than 0.8 for both annual and seasonal averages, being higher than 0.75 for the nationally averaged series (Supplementary

Figure 2). These findings strongly suggest that SUN data could be a coherent measure of the effect of GR on the evolution of LST over Spain.

Figure 4: Relationship between the 9 monthly GR series (w/m^2) and their corresponding SUN series (hours/day) from the gridded dataset.

2.5. Land cover

To characterize the relationship between LST changes and the land cover (LC), we used the Corine 2000, which is the standard European LC map for Europe (Gallego et al., 2011). We selected this dataset due to its high spatial resolution. Furthermore, the year of the map (i.e.,

2000) represents approximately a mid-point in the study period (1981-2015), which allowed for identifying the general land cover conditions over the entire study period. The Corine 2000 consists of 44 land cover categories/classes that represent all possible landscape conditions. Here, it is noteworthy indicating that we grouped the available categories in the Corine dataset into 10 classes that represent the main land cover types across the peninsular Spain. We decided to retain only seven of these types, which cover a major percentage of the study area. The selected LCs include agricultural lands (e.g. irrigated, non-irrigated and permanent crops areas), forest pastures (e.g. coniferous, broad leaved and mixed forest), besides sparsely vegetated areas. Overall, the selected categories are listed in Supplementary Table 2, with the percentage of surface represented by each of them across the study domain, while their spatial distribution is illustrated in Supplementary Figure 3.

3. Methods

The nonparametric Mann-Kendall Tau test was applied to test trend significance of seasonal and annual LST series. This statistic is more robust than parametric tests, as it is not sensitive to the presence of outliers and does not assume any prior distribution of the data (Lanzante, 1996). The values of Tau measure the degree to which a trend is consistently increasing or decreasing, where positive (negative) values indicate an increasing (decreasing) trend of LST. For each seasonal and annual series of LST, the significance of trends was assessed at the 95% confidence level ($p < 0.05$). To limit the possible influence of serial temporal autocorrelation on trend detection, we applied a modified Mann-Kendall trend test, which returns the corrected p-values after accounting for temporal pseudo-replication (Hamed and Rao, 1998).

In order to define the amount of change in LST, we used a linear regression analysis between the series of time (independent variable) and LST series (dependent variable). The slope of

each model indicates the amount of change in LST per year, with higher slope values suggesting greater LST changes and vice versa.

To explore the influence of the different land and meteorological variables on the observed trends in LST between 1982 and 2014 (the period of common information for all different variables), we applied a multiple linear regression algorithm in which the dependent variable (LST) was modeled according to the evolution of Tmax (as a measure of global warming forcing), SUN (as a measure of the radiative forcing) and NDVI (as a measure of land cover changes). Following this procedure, we estimated the standardized beta coefficient, which indicates the relative contribution of each variable to LST evolution.

Recalling that some of the independent variables used in this study are interrelated, a conservative value of 0.01 was set as a threshold for any variable to enter the stepwise regression procedure, as recommended by Hair et al. (1998). In addition, a condition index test was also applied to the regression models, with the aim of flagging those models with high uncertainty, as a consequence of the presence of multicollinearity in the data. This test recommends the use of those models with less number of parameters.

While this approach allows for calculating how LST is driven by possible temporal variability and trends in other variables (e.g. Tmax, NDVI and SUN), it can also determine residuals, as the difference between the observed and predicted LST for each pixel within the study area. These residuals allow for quantifying and characterizing the differences between the observed and predicted evolution of LST according to the evolution of these three variables. We calculated series of model residuals for each pixel considering seasonal and annual series. Finally, the Mann-Kendall Tau test was used to assess changes in residuals series.

4. Results

4.1. Temporal evolution of LST

Figure 5 shows the evolution of the average seasonal and annual LST in the peninsular Spain between 1982 and 2014. At both seasonal and annual scales, LST shows high inter-annual variability. Annually, there is a statistically significant ($p < 0.05$) increase on the order of $0.71^{\circ}\text{C decade}^{-1}$, which can be attributed to the strong increase recorded during summer months ($1.53^{\circ}\text{C decade}^{-1}$). In spring and autumn, the magnitude of change is more or less similar to that found at annual scale (0.72°C and $0.53^{\circ}\text{C decade}^{-1}$, respectively), whereas changes are markedly weak during wintertime ($0.07^{\circ}\text{C decade}^{-1}$, $p > 0.05$).

Figure 5: Temporal evolution of the seasonal and annual averages of LST between 1982 and 2014.

Figure 6 depicts the spatial patterns of LST trends for the same period, while Table 1 summarizes the surface area represented by both positive and negative trends grouped according to their statistical significance. At the annual scale, positive significant trends

almost dominate across the study domain (76.7%). The only exception is found in some regions located in the northern part of Spain, where positive, but non-significant, trends are observed. Negative trends occur in a very small area (0.4%) of the Central and the Iberian systems, besides the greenhouses area of Almeria, in which it is difficult to interpret LST trends. At seasonal scale, there are noticeable differences. Summer shows a general positive trend in the LST, where 77.2% of the study area showed a statistically significant positive trend: a percentage quite similar to that observed for the annual series. Nevertheless, the observed spatial patterns reveal some interesting findings, where negative trends are recorded in the areas of the Ebro, Duero and Guadiana basins. These basins are characterized by the transformation of non-irrigated cultivations into irrigated cultivations, inducing a decrease in LST over the last decades. For spring and autumn, positive trends prevail in almost the whole study area, with 52.2% and 39.2%, respectively. In contrast to other seasons, statistically non-significant trends dominate over large portions of the peninsula, with the exception of some areas with positive trends, especially in eastern and central Spain.

Figure 6: Trends in the seasonal and annual averages of LST between 1982 and 2014.

Table 1: Percentage of surface area represented by each of LST trend categories

	Positive trends		Negative trends	
	p<0.05	p>0.05	p<0.05	p>0.05
Annual	76.7	19.7	0.4	3.2
Spring	52.2	43.8	0.3	3.7
Summer	77.2	20	0.2	2.6
Autumn	39.2	51	0.3	9.5
Winter	8.4	52.4	2.4	36.8

Figure 7 illustrates the magnitude of change in LST during the last three decades. The study area showed high spatial variability, with respect to both seasonal and annual scales. Summer season showed an exceptional increase ($>5^{\circ}\text{C}$) in large areas of the peninsula, especially in the southern and central regions. In spring and autumn, the increase is mostly recorded in areas of the Ebro and Guadalquivir basins, but also in the central and eastern areas of Spain. Spatial differences are more pronounced at the annual scale, with no changes and even a slight decrease in the areas of northern Spain. Again, the spatial patterns of the annual LST change are more consistent with changes observed during spring, summer and autumn rather than in winter.

Figure 7: Spatial distribution of the seasonal and annual magnitude of change in LST between 1982 and 2014.

4.2. Links of LST to maximum air temperature and sunshine duration

We linked changes in LST with those of Tmax and SUN. The inter-annual variability of Tmax between 1982 and 2014 at both seasonal and annual scales is illustrated in Supplementary Figure 4. As shown, the magnitude and statistical significance of the observed

trends of T_{max} are different from those of LST. Annually, there is an increase of 0.18 °C decade⁻¹, which is statistically non-significant. In contrast, significant increases are found for spring and summer (0.40°C and 0.32°C decade⁻¹, respectively). Spatially, T_{max} showed a general positive trend in almost all the area at the annual scale as well as in spring and summer (Supplementary Figures 5 and 6). Nevertheless, significant trends are mostly recorded in the western and eastern parts of Spain, while non-significant trends are distributed over the central, northern and southern areas. Overall, positive and statistically significant T_{max} trends are recorded only over 28.7% of the study domain (Supplementary Table 3). The dominant positive trends of T_{max} are mainly associated with the general positive and significant changes during spring and summer. There is a dominant (>50%) and significant increase of T_{max} over the northern and eastern regions of Spain during spring. In comparison, significant and positive changes of T_{max} during summertime are recorded in 40.8% of the study area, mainly in the southern regions. In contrast, insignificant trends are observed across vast areas of the peninsula during winter and autumn.

Figure 8 summarizes the relationship between seasonal and annual variability of T_{max} and those of LST for the peninsular Spain. The different scatterplots reveal a closer association between LST and T_{max} during transitional seasons (i.e. spring and autumn) and annually. The higher correlation found during winter and autumn may be attributed to the influence of the land cover, which is somehow minimized during these seasons, as areas are likely wetter and more homogeneous. The only exception corresponds to summertime, where the correlation is statistically non-significant ($p > 0.05$). Spatially, a similar high agreement between T_{max} and LST was observed annually and seasonally, except for summer. In summer, the correlation between LST and T_{max} is dominantly positive across the majority of the study area, though being statistically significant only in the northern and northeastern regions. Supplementary Figure 7 suggests a dominant positive and statistically significant

correlation between Tmax and LST during spring, autumn and annually, representing 89.8, 94.5 and 77.1% of the total area of the peninsular Spain, respectively) (Supplementary Table 4).

Figure 8: Relationship between seasonal and annual averages of LST and those of Tmax.

Nevertheless, although the correlation between LST and Tmax is generally positive and statistically significant across the study domain, we found that the observed trends of both Tmax and LST do not agree spatially (Supplementary Figure 8). This finding implies that while there is a generally high agreement between the temporal variability of LST and Tmax, other local factors (e.g. vegetation, land use, topography, and residual orbital drift) may influence the dependency between Tmax and LST.

We also analyzed the relationship between LST and SUN. We found that SUN shows a significant increase at the annual scale on the order of $0.22 \text{ h. decade}^{-1}$ between 1982 and

2014 (Supplementary Figure 9). This increase can mainly be explained by the strong increase during summer months ($0.34 \text{ h. decade}^{-1}$). For other seasons, SUN showed an increase, though being statistically non-significant ($p > 0.05$), particularly during spring and winter. This pattern coincides closely with our results on GR trends, calculated for the available 9 stations over the study domain (Supplementary Figure 10), where the increase at the annual scale was 3.7 Wm^2 , mostly explained by the strong increase during summer months (9.2 Wm^2). In accordance with SUN trends, our findings reveal statistically significant trends in GR during spring and winter.

There is a significant relationship between the temporal evolution of LST and SUN between 1982 and 2014. Figure 9 illustrates the relationship between the inter-annual variability of LST and SUN over the study domain. The correlation between LST and SUN is generally positive (> 0.42) and significant ($p < 0.05$), suggesting that irrespective of the season, higher SUN values correspond to higher LST. This association can be clearly seen during summertime, where the anomalous highest increase in LST and SUN was observed, with positive and statistically significant correlation between the two variables.

Figure 9: Relationship between the seasonal and annual averages of LST and those of SUN.

The analysis of trends and changes in SUN indicates a general increase of the radiative forcing during the past three decades. At the annual scale, positive significant trends are found for more than 96% of the study area, which can mainly be attributed to the significant increase of SUN during summer (75.97 %) and autumn (58.27%) seasons (Supplementary Figures 11 and 12 and Supplementary Table 5).

In addition, we analyzed the spatial correlation between the seasonal and annual SUN and the gridded series of LST over the study domain. Results reveal a general positive and statistically significant correlation for the whole peninsula seasonally and annually, with few spatial

differences (Supplementary Figures 13 and 14 and Supplementary Table 6). These positive and significant correlations indicate that trends in LST could largely be related to in the spatial variations in radiative forcing, particularly during summertime. This finding is supported by our observation of the spatial association between regions of higher changes in LST and those of rapid increases in SUN (Supplementary Figure 15).

4.3. Links between LST and land cover types and NDVI

NDVI shows a clear increase in peninsular Spain from 1982 to 2014, which is statistically significant at both seasonal and annual scales (Supplementary Figure 16). NDVI trends are dominantly positive in most of the study domain (Supplementary Figure 17). In particular, more than 90% of the peninsular Spain showed positive and significant changes in the NDVI at the annual scale (Supplementary Table 7). In any case, summer is the season with less significant changes, particularly in the central and southern regions. These areas show non-significant and even negative NDVI trends, which coincide with the higher increase in LST during summer months.

The correlation between LST and NDVI shows important spatial differences at both seasonal and annual timescales (Supplementary Figure 18), although correlations are generally non-significant (Supplementary Figure 19) except for summer (Figure 10). Exceptionally, spring and summer show a positive correlation in the Cantabrian region and the Pyrenees to the north, while negative correlations dominate across larger areas in the southern, western and central portions of the Ebro basin. Interestingly, at the annual scale, there are contrasted correlations between the northern regions and the main mountainous areas (positive) and the southern regions, the main hydrological basins in the north (e.g. Duero and Ebro) and Guadalquivir in the south (negative).

Figure 10: Relationship between the seasonal and annual averages of LST and those of NDVI.

Nevertheless, although the correlations between NDVI and LST are not statistically significant in large areas between 1982 and 2014, the spatial patterns of LST changes are strongly related to NDVI changes. In comparison to Tmax and SUN, the spatial patterns of LST changes are mostly related to the spatial patterns of NDVI changes. Figure 11 shows the relationship between the observed magnitudes of change in LST and those of the NDVI between 1982 and 2014. The scatterplots indicate a strong relationship between LST and NDVI changes at both seasonal and annual scales. The majority of pixels showing increases in NDVI correspond to increases in LST, with LST increases being larger in summer than in winter. The correlations between NDVI and LST changes are negative at seasonal and annual timescales, with values ranging between -0.38 (winter) and -0.65 (summer) ($p<0.05$). These patterns clearly illustrate that an increase in the vegetation activity is favoring a reduction in

LST; this finding is particularly evident during summertime, where the available solar radiation is much more important.

Figure 11: Scatterplots representing the spatial relationship between the observed magnitude of changes in LST and those of NDVI for 1982-2014. The colors represent the density gradient of points, with red showing the highest density.

The type of land cover (LC) also seems to have a strong influence on LST changes. We calculated the differences in the average magnitude of change of LST as function of the dominant land cover types in the peninsula as well as the percentage of surface showing significant trends in each type (Figure 12 and Table 2). Areas with permanent crops show the most pronounced change in LST during the last 33 years at both seasonal and annual scales (3.1°C at the annual scale). In contrast, forests exhibit the lowest LST changes. In comparison

to crop areas, the average magnitude of change recorded in the different forest types was generally less than 40%.

Figure 12: Mean and standard error of the LST change recorded in the selected LC types

Table 2: Percentage of surface dominated by significant trends in LST as a function of the selected LC types.

	Percentage of positive significant trends (%)					Percentage of negative significant trends (%)				
	Annu al	Sprin g	Summ er	Autum n	Wint er	Annu al	Sprin g	Summ er	Autum n	Wint er
Irrigated areas	79.5	59.3	77.2	54.7	12.4	0.2	0.3	0.4	0.6	0.6
Non-irrigated areas	86.4	56.4	85.8	48.4	9.9	0.1	0.1	0.2	0.2	1.4
Permanent crops	88.3	59.6	90.2	55.2	12.6	0.0	0.0	0.0	0.0	1.1
Coniferous forest	58.3	39.3	63.0	23.1	7.3	0.9	0.7	0.2	0.4	5.0
Broad leaved forest	68.9	45.5	69.6	24.3	4.1	0.5	0.3	0.2	0.3	2.5
Mixed forest	59.4	57.4	59.4	10.8	3.7	1.0	0.5	0.4	0.4	7.0
Pasture and sparsely vegetated areas	69.6	48.5	70.8	31.6	6.1	0.6	0.4	0.2	0.3	3.3

4.4. Statistical modeling of LST based on the other variables

Here, we applied a multiple linear regression model to characterize the relationship between LST changes and the evolution of Tmax, SUN and the NDVI recorded at a grid scale (see details in the methodology section). Figure 13 shows the spatial distribution of the R^2 obtained from the seasonal and annual models. Although, large areas of the peninsular Spain show noticeable percentage of LST variability, as explained by the statistical model especially the west and the Ebro basin in Spring, the model fails to explain LST variability in some other areas especially in summer season. These results suggest that LST evolution between 1982 and 2014 can be independent of the evolution of one or more of the three investigated variables. The possible remaining orbital drift could be responsible for this behavior.

Figure 13: Seasonal and annual R^2 for the multivariate LST models created from T_{max} , NDVI and SUN.

In addition, we studied the temporal evolution of the average residuals obtained from the seasonal and annual regression models (Figure 14) to quantify how the statistical model fails to explain part of LST evolution. Annually and during winter and autumn, the residuals do not show any significant trend. While these residuals show a general increase, this increase is much lower than that recorded for the observed LST series. This finding suggests that although the statistical model do not explain adequately LST evolution in some cases (mainly summer season), large percentage of the magnitude of change observed in the LST series can be explained by the evolution of the independent variables used in the model. In summer, where LST is probably independent of the three studied variables, the positive evolution in

model-residuals could be mainly explained by the noticeable decrease of LST around 1990, in comparison to the observed evolution of Tmax, NDVI and SUN. On the other hand, positive and statistically significant trends are found during summer and spring seasons, which demonstrates that the observed LST trend is higher than that of the independent variables. Nevertheless, the evolution of the residuals is low and the magnitude of the unexplained trend does not show any remarkable increase.

Figure 14: Evolution of the LST's residuals from the seasonal and annual regression models considering Tmax, SUN and NDVI as independent variables

Spatially, the majority of the study domain have experienced statistically non-significant residual trends (Supplementary Table 8). The significant trends are mainly concentrated in some areas in the center, the Duero basin and some areas to the south, particularly during summer months where the highest increase is recorded. However, areas of the north are mainly showing negative trends in model residuals (Supplementary Figure 20 and Supplementary Figure 21).

Finally, and despite the possible effect of orbital drift and the independence of LST evolution from the three studied variables in some cases, we analyzed the relative importance of the different independent variables (Tmax, NDVI and SUN) in explaining the trends of LST across the peninsular Spain by means of the standardized beta coefficients (Supplementary Figures 22 to 24). At the seasonal and annual scales, Tmax and SUN seem to be more important than NDVI in terms of explaining the observed variability of LST. Nevertheless, although this finding is generally valid for the whole study domain at spatial scales ranging from local to regional, the NDVI may contribute significantly to modulate LST. This is clearly identified during summer, where areas to the south and east show high negative Beta coefficients, suggesting that LST increase in these areas is enhanced by NDVI decrease. Tmax is another key variable explaining LST trends during spring, autumn and summer (northern Spain). Nevertheless, in summer and annually, the observed trend in SUN is the main explanatory factor of LST evolution. This feature is mostly identified in areas of the center, south, southeast and the Ebro basin; these areas are generally characterized by low vegetation coverage.

5. Discussion and conclusions

5.1. LST trends

This study analyzed long-term trends in Land Surface Temperature (LST) over peninsular Spain during the last three decades. Changes in LST were also linked to changes in maximum air temperature, solar radiation and vegetation activity (as represented by the NDVI). With some exceptions as in the Almeria region, where the high albedo of the greenhouses has a negative radiative forcing cooling effect (Campra et al., 2008), LST showed a significant increase between 1982 and 2014. The average annual increase was on the order of $0.71\text{ }^{\circ}\text{C decade}^{-1}$, with a rapid increase during summertime ($1.53\text{ }^{\circ}\text{C decade}^{-1}$). The LST increase in

spring and autumn was also positive, although the magnitude of change was much lower than in summer.

There are very few studies that analyzed the evolution of LST in the Mediterranean region. Nonetheless, these studies show contradictory results to what we found for Spain. For example, Julien et al. (2006) analyzed changes in LST values over Europe between 1982 and 1999 using the Pathfinder AVHRR Land (PAL) dataset. They found a general decrease on the order of more than 2.5°C in southern Spain and in other areas of the Mediterranean. These differences might be linked to the strong orbital drift that characterized the PAL dataset, given that some contradictory results emerged from the PAL analysis. For example, PAL showed a remarkable decrease in LST over areas of southern Spain, which are characterized by a dominant NDVI decrease.

5.2. Links to radiative forcing

The strong increase of LST during summer season is coherent with observations of the recent radiative forcing affecting Spain, mainly during this season. Summer sunshine duration (SUN) showed a strong increase in Spain between 1982 and 2014. Although our assessment of this association was based on the available limited sunshine duration records during the study period, several studies confirmed our results, but using homogenized GR series (e.g. Sánchez-Lorenzo et al., 2013, 2015). Indeed, this association can mostly be related to the decrease of cloud coverage and aerosol concentrations, particularly during summer (Mateos et al., 2014). Here, we found that the annual SUN showed an increase of 0.22 h.decade⁻¹, which was more consistent with the observed changes during summer (0.34 h.decade⁻¹), as well as the observed trends in the available GR stations (3.7 Wm⁻² decade⁻¹ and 9.2 Wm⁻² decade⁻¹). This is a very strong increase in the available surface radiation since - in a simple framework-

the Earth surface has to warm by about 1°C to compensate for an increase in (solar) energy at the surface of 5 W m²(Wild, 2016).

We must stress that it is difficult to directly associate an increase of the incoming GR to a direct land surface warming, given that there are several factors affecting the direct conversion of the solar radiation to temperature (e.g. reflectance of land surfaces, soil type, soil water content, land cover, vegetation type, land emissivity, atmospheric longwave emission, evapotranspiration, sensible heat flux, etc.). Nevertheless, it is also very relevant that between 1982 and 2014, we found an average increase of 32.2 W m² in GR during summer for the entire Spain, which is similar to the observed increase in SUN and even higher at particular meteorological stations. A direct transformation of this available energy to temperature would lead to an increase higher than 6 °C, which is even higher than what we obtained for summer LST across the whole peninsular Spain.

5.3. Influence of land cover changes

Our results indicate a strong spatial coherence between LST and NDVI changes. The areas showing the main increase in LST were in agreement with those exhibiting either no changes or a dominant decrease in the vegetation coverage. Given the strong relationship between LST and the NDVI confirmed in this study, as in other previous studies worldwide (e.g. Kogan, 1997; Weng et al., 2004; Chen et al., 2006), it is expected that areas that showed a decrease in the vegetation coverage were affected by a certain increase in LST, given the lower land capacity to regulate heat conditions associated with radiative forcing.

Thus, the areas with a higher increase in the NDVI values exhibited the lowest increase in LST. The areas with the largest increase in NDVI (higher than 0.2 NDVI units between 1982 and 2014) showed a dominant decrease in LST during summers of the same period. The negative correlation between LST and NDVI changes was also recorded in spring, autumn

and at the annual scale. These results confer great reliability to the obtained spatial patterns in the magnitude of change of LST. Also, they stress that, in addition to radiation forcing, changes in the vegetation coverage are key drivers of LST, determining the spatial differences of LST trends. Thus, the most important changes in LST, with LST increases higher than 10°C between 1982 and 2014, were recorded in the areas that showed the strongest decrease in NDVI values.

5.4. Uncertainty in the estimations

Herein, we also stress that our estimations of LST, based on the AVHRR imagery data, can have some uncertainty and it is thus difficult to consider them as completely valid for defining a certain magnitude of LST increase across the peninsular Spain. This uncertainty is mainly related to orbital drifts of the NOAA-AVHRR satellites, which could affect the final observational trends (Sobrino and Julien, 2016). For example, although robust statistical corrections have been implemented in the dataset, it still a jump in 1995, followed by more or less stable temperatures have been identified in the dataset. In 1995 NOAA-14 replaced the already failing NOAA-11 after more than six years of service and the observed change in 1995 could be caused by this. Here, we applied a statistical model to diminish this effect. Nonetheless, the model itself could also be impacted by other sources of uncertainty. This can probably include land cover changes throughout the entire period that may dismiss the effect of solar/observation angles and also the possible non-linear effects of these angles on LST. Nonetheless, we still believe that our model was skillful somehow in correcting the drifting and accordingly provided more accurate trends. Moreover, and irrespective of the absolute magnitude of LST trends, the strong coherence of the spatial distribution of the observed changes and the connection with NDVI changes seems to support changes in LST across Spain. In addition, it is not only the high agreement between the magnitude of LST trends and

the observed SUN trends, which explains the general LST warming over Spain during the last three decades, but it is also the strong coincidence between the seasonal patterns of SUN trends and LST trends, particularly during summer

The confidence in the obtained LST trends during summer is also reinforced by the spatial differences recorded in trends, in addition to the differences found between land cover types. All selected land cover types showed a positive and significant LST increase, but the magnitude of this increase was much higher in the dryland non-permanent agricultural areas, which are usually harvested during summer, where soil is dominantly nude. In contrast, in well-developed forest types, the magnitude of LST was much lower (4°C on average) among forests and dryland agricultural areas during summer.

5.5. Links to global change processes

In the Iberian Peninsula, drought conditions increased noticeably over the past five decades, mostly associated with precipitation decrease (Vicente-Serrano et al., 2013), as well as an increase in the Atmospheric Evaporative Demand (AED) related to an air temperature increase and the decrease of the relative humidity (Vicente-Serrano et al., 2014a, b, c). Thus, summer records the highest increase in the AED among the different seasons of the year (12 mm decade⁻¹) (Vicente-Serrano et al., 2014a). Under these conditions of high aridity and water stress (lower precipitation, higher AED, and more severe drought events), areas with low vegetation coverage and low capacity to retain water would warm up. This is simply due to the observed increase in the radiative forcing, given that no heat can be dissipated by evapotranspiration and they also have low heat capacity. Thus, as observed in this study, it would be expected that these areas warm more than areas characterized by more humid conditions and dense vegetation coverage.

In the humid areas of northern Spain, which are characterized by a high vegetation coverage and a general increase of the vegetation activity (Hill et al., 2008; García-Ruiz et al., 2012), the increase of SUN had a lower effect on LST, in comparison to central and southern regions of Spain as well as the low vegetated areas of the Ebro basin. These dry regions have experienced increased aridity in the last decades (Vicente-Serrano et al., 2013). As such, it is reasonable to assume that none of the additional energy available from GR would go into additional evaporation and most of this energy would be transformed in sensible heat flux. However, although some uncertainty could be associated with the satellite imagery data used in this work, particularly orbital drift, the trends found for GR suggest a reasonable increase in LST, mainly during summer. The spatial patterns of these trends would be modulated by the spatial distribution of land cover and the trends in vegetation activity.

The observed LST trends and the spatial patterns obtained in this study can contribute to better understanding of the recent ecohydrological processes in Spain. The general aridification that characterizes the recent climate evolution in Spain (Vicente-Serrano et al., 2014b) would agree with what would be expected in LST under strongly increased incoming GR. All these processes would agree with the general increased tree-growth decline and desertification processes observed in some water limited systems in Spain (Carnicer et al., 2011; Vicente-Serrano et al., 2012; Camarero et al., 2015a). Nevertheless, we would also like to stress that several uncertainties still remain, given that the general climate aridification and increased environmental stress, clearly identified by the LST trends, seem to coincide well with the general observed increase in vegetation coverage and activity across large areas of Spain (Lasanta et al., 2005; Hill et al., 2008). This pattern seems to be paradoxical under the general aridity scenario that affects the region.

A possible explanation that reconciles the observed trends is that positive vegetation activity is mainly recorded in mountain areas (Vicente-serrano et al., 2004; Lasanta et al., 2005; Hill

et al., 2008; Del Barrio et al., 2010). Karnieli et al. (2010) showed that when water is the limiting factor of vegetation growth, the LST–NDVI correlation is expected to be negative. However, when energy is the limiting factor, as in higher latitudes and most elevated elevations at the beginning of the growing season), a positive correlation exists between LST and NDVI. In Spain, mountain areas are characterized by high precipitation values and positive climatic water balances. However, while these areas are affected by decreasing precipitation and higher AED, water availability is still enough to maintain more developed vegetation coverage. Thus, these areas are still showing water surplus conditions. Other factor that could explain this paradoxical pattern is that under the current scenario of increased greenhouse gasses and CO₂ concentrations, the vegetation would be less sensitive to water stress given to CO₂ fertilization (Field et al., 1992; Canadell et al., 2007), which would increase the efficiency in the use of water by vegetation, even in arid ecosystems (Donohue et al., 2013; Swann et al., 2016). Nevertheless, further research is needed to validate this hypothesis, given that studies in humid areas of northern Spain suggest limited evidence of the impact of CO₂ fertilization on forest growth (Camarero et al., 2015b).

In any case, under the current scenario of land abandonment and natural revegetation (García-Ruiz and Lana-Renault, 2011), the high soil water availability in the humid forests of the Spanish mountain areas could explain the general increase of the NDVI, and the lower increase of LST during summer months, in comparison to other regions under a radiation forcing scenario. This pattern would be also in agreement with water resources observations in most of the mountain areas across Spain (Lopez-Moreno et al., 2012; Lorenzo-Lacruz et al., 2012b). Herein, although the current water availability can be sufficient to favor an increase in vegetation coverage and activity assuming higher atmospheric CO₂ fertilization, air temperature, available radiation, combined with the increased water consumption by forest

would explain reduced water availability downstream (Begueria et al., 2003; García-Ruiz et al., 2012).

The observed pattern in mountain areas is completely different to that observed in flat areas of dry Spain. These areas are characterized by very negative climate water balances and low vegetation coverage. In these areas, vegetation activity did not show any dominant positive trend, but they even showed a decrease in vegetation coverage across large areas, providing evidence of land degradation processes (Del Barrio et al., 2010; Vicente-Serrano et al., 2012). Thus, a higher GR could be a reinforcing stressing factor in the very dry soils that characterize these regions during summer months and thus explain the strong LST positive trends observed in these regions since 1980s.

In summary, according to the observed trends and the discussed mechanisms in this study, we would suggest a model in which the GR increase in principle enhances LST changes. This feedback is further supported by the impact of vegetation activity (Figure 15). Following this model, the regions are differently controlled by radiation or water and the NDVI shows a response to both climate and management factors. In areas or periods with water limitation, the increase in LST and GR will reduce NDVI and this will further exacerbate the direct increases in LST due to GR (Positive feedback). If due to human activities (e.g., reforestation) or CO₂ fertilization NDVI increases, then this will partially compensate the LST increase (negative feedback on LST), so the reduction in LST increase is larger for larger NDVI changes. On the contrary, land degradation or NDVI losses will amplify the LST increase even more. Nevertheless, in radiation controlled areas/times (e.g. the Atlantic Spain and mountainous areas), the increase in GR and LST will enhance plant growth and NDVI, which in turn will tend to partially compensate LST increase.

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Highlights

- All satellite data from the NOAA-AVHRR product (July 1981-June 2015) was considered.
- LST showed a significant increase in the peninsular Spain between 1982 and 2014.
- Strong spatial coherence between LST and NDVI changes has been found.
- The average increase of LST during summer was on the order of $1.53\text{ }^{\circ}\text{C decade}^{-1}$.
- The increase of LST during summer is coherent with observations of radiative forcing.