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Assessment of vapor pressure deficit variability and trends in Spain and possible connections with soil moisture

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ABSTRACT

The Vapor Pressure Deficit (VPD) is one of the most relevant surface meteorological variables; with important implications in ecology, hydrology, and atmosphere. By understanding the processes involved in the variability and trend of the VPD, it is possible to assess the possible impacts and implications related to both physical and human environments, like plant function, water use efficiency, net ecosystem production, atmospheric CO_2 growth rate, etc. This study analysed recent temporal variability and trends in VPD in Spain between 1980 and 2020 using a recently developed high-quality dataset. Also, the connection between VPD and soil moisture and other key climate variables (e.g. air temperature, precipitation, and relative humidity) was assessed on different time scales varying from weekly to annual. The objective was to determine if changes in land-atmosphere feedbacks connected with soil moisture and evapotranspiration anomalies have been relevant to assess the interannual variability and trends in VPD. Results demonstrate that VPD exhibited a clear seasonality and dominant positive trends on both the seasonal (mainly spring and summer) and annual scales. Rather, trends were statistically non-significant ($p > 0.05$) during winter and autumn. Spatially, VPD positive trends were more pronounced in southern and eastern of Spain. Also, results suggest that recent trends of VPD shows low contribution of variables that drive land-atmosphere feedbacks (e.g. evapotranspiration, and soil moisture) in comparison to the role of global warming processes. Notably, the variability of VPD seems to be less coupled with soil moisture variability during summertime, while it is better interrelated during winter, indicating that VPD variability would be mostly related to climate variability mechanisms that control temperature and relative humidity than to land-atmosohere feedbacks. Overall, our findings highlight the importance of assessing driving forces and physical mechanisms that control VPD variability using high-quality climate datasets, especially, in semiarid and sub-humid regions of the world.

1. Introduction

Vapor Pressure Deficit (VPD) is one of the most important surface meteorological variables, mainly for plant physiology, particularly leaf diffusive conductance, plant productivity, and carbon uptake (Breshears et al., 2013; Grossiord et al., 2020; Medlyn et al., 2001) and forest fires (Balch et al., 2022). It is well-established that VPD plays a key role in modulating photosynthesis and carbon uptake and growth (Breshears et al., 2013; Eamus et al., 2013; Kimm et al., 2020; Lendzion and Leuschner, 2008; Sulman et al., 2016). Moreover, VPD has significant hydrological implications, as it is one of the controlling variables of atmospheric evaporative demand (AED) (Allen et al., 1998).

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Specifically, combined with wind speed, VPD controls the aerodynamic component of atmospheric demand, which is the most influential factor in explaining recent trends and future projections in AED (Vicente-Serrano et al., 2020; Wang et al., 2012). AED has significant environmental and hydrological implications that impact plant transpiration (Massmann et al., 2019), land water availability (Friedrich et al., 2018; Wang et al., 2018), as well as the severity of hydrological, agricultural, and ecological droughts (Dai et al., 2018; Vicente-Serrano et al., 2020).

VPD is computed simply as the difference between the saturation (e_s) and the actual (e_a) vapor pressure, which are obtained from near-surface air temperature (T) and air humidity. As such, the temporal variability and changes of VPD depend largely on these two variables. Numerous studies indicate that VPD changes are driven by changes in both atmospheric conditions and land-atmosphere feedbacks (Ambika and Mishra, 2020; Yuan et al., 2019; Zhou et al., 2019). Globally, VPD is increasing (Wang et al., 2012; Yuan et al., 2019) because, under global warming there is an increase in e_s that is not paired with equal increases in e_a. Other studies demonstrate that the varying warming rate between land and oceanic regions is also a key driver of VPD trends, mainly due to sub-saturation of moisture content in the air that comes from the oceans to continents (Byrne and O'Gorman, 2018; Sherwood and Fu, 2014). This mechanism is responsible for the recent dominant observed decrease in relative humidity over the majority of mild-latitudinal land areas of the North hemisphere in the past decades (Vicente-Serrano et al., 2018), and is likely to contribute to the projected relative humidity decrease in future scenarios (Douville et al., 2021).

However, although long-term VPD trends are largely influenced by global warming-related direct and indirect mechanisms, they can also be impacted by other drivers that control air temperature and air humidity. There are a number of factors to consider, including atmospheric circulation variability, which has a significant impact on the spatio-temporal variability of air temperature and air humidity (Martens et al., 2018). As such, it is expected that atmospheric conditions corresponding to high VPD are favourable for precipitation deficits and drought.

Also, soil moisture can be seen as a main driver of VPD changes (Seneviratne et al., 2010), particularly during the warm season (Zhou et al., 2019). This is related mainly to the Bouchet's complementary relationship (Bouchet, 1963; Brutsaert and Parlange, 1998), given that, in the absence of air advection, VPD would be controlled by land-atmosphere feedbacks, which are determined by the partition of total heat flux between latent and sensible fluxes that are driven primarily by soil moisture variations. Specifically, under dry soils, land evapotranspiration (E_t) would be limited, so latent heat flux decreases and sensible heat increases. This mechanism can reduce water flow from land to the atmosphere, thereby inducing an increase in air temperature, a reduction in relative humidity, and finally an enhancement of VPD.

Land-atmosphere feedbacks have recently been highlighted as a key factor that contributes to VPD variability across different regions worldwide (Ambika and Mishra, 2020; Liu et al., 2020a; Stegehuis et al., 2021). The VPD changes were mostly explained by air temperature (Fischer et al., 2007; Hirschi et al., 2011) and relative humidity changes (Zhou et al., 2019) associated with soil moisture variations.

Unfortunately, a comprehensive assessment of VPD changes over Spain and their driving forces is still lacking at the national scale, albeit with the notion that variability and trends of VPD could have direct impacts on agricultural, ecological and hydrological systems in the country. Few studies have assessed the impacts of VPD changes over Spain. For example, Villalobos et al. (2000) assessed the role of VPD and soil surface evaporation in olive orchard crop performance over southern Spain. More recently, Larsen (2021) evaluated the impacts of increased VPD on *Pinus halepensis* Mill, which is one of the most common species in eastern Spain, demonstrating how transpiration patterns and soil-water balance are strongly dependent of VPD changes.

This study aims to (i) analyse recent changes and variability of VPD in Spain using the densest quality-controlled network of meteorological observations for the period 1980–2020 and (ii) identify the possible mechanisms controlling this variability and change, which features the diverse climatic conditions, particularly in light of the country's large coverage of semi-arid climate conditions. In particular, this study assesses the possible role that land-atmosphere feedbacks, driven by soil moisture and evapotranspiration anomalies, may have on VPD variability and trends in comparison to the role of global warming processes.

2. Datasets description

A complete register of daily maximum and minimum air temperatures, daily mean dew point temperature, and precipitation for Spain between 1980 and 2020 was provided by the Spanish National Meteorological Agency (AEMET). Data were subjected to a rigorous quality control and homogenization procedure as outlined in Tomas Burguera et al. (2016). Herein, it should be noted that the first day of each year can fall on different days, and this propagates throughout the year, so it was not possible to use “week” as the reference time step for calculations. Also, leap years may have contributed to the inconsistency of the periods being compared. As a result, each month was divided into four artificial “weekly” periods: the first from the 1st to the 8th day, the second from the 9th to the 15th day, the third from the 16th to the 22nd day, and the fourth from the 23rd day to the end of the month. This approach enabled interannual comparisons amongst sub-monthly periods, retaining the VPD variability better, compared to the data on a monthly scale. The weekly data were tested for possible temporal inhomogeneities using the Standard Normal Homogeneity Test (SNHT) (Alexandersson, 1986). Fig. 1 shows the spatial distribution of the complete series of air temperature and dew point temperature available for 1980–2020. As illustrated, the stations are evenly distributed over space, albeit with improved spatial coverage for air temperature and precipitation in particular.

Prior to calculating VPD, weekly data for input variables were interpolated to a common spatial resolution of 1 km^2 using the universal Kriging interpolator, which accounted for elevation as an auxiliary variable. Further details about the development of this dataset can be found in Vicente-Serrano et al. (2017). Fig. 2 summarizes the statistical validation results for the interpolated maximum and minimum air temperatures and dew point temperature. The accuracy was measured using the Willmott's D agreement index (Willmott et al., 2012). This statistic is calculated from the estimations obtained by means of a Jacknife approach based on withholding, in turn, one station out of the network, estimating regression coefficients from the remaining observatories, and calculating the difference between the predicted and observed value for each withheld observatory (Phillips et al., 1992). The evolution of D over the period 1980–2000 suggests the level of agreement between the observed and predicted data over time. These calculations were made for each of the three input variables. The values of the D agreement index vary from 0 to 1, with values close to one indicating high agreement and minimal bias. Overall, results demonstrate the high accuracy of the weekly 1 km^2 gridded dataset used to compute VPD. The seasonal and annual series of observations and those interpolated using the Jacknife approach (in which the predicted series are independent of the series of every meteorological station) show an excellent agreement. Fig. S1 shows the temporal evolution of these average series and the average series of observations based on the available meteorological stations and they show the same evolution, with very few and small differences amongst them. Thus, the magnitude of change between the series of observations and the series interpolated by the Jacknife approach are basically similar at the seasonal and annual scales (Fig. S2).

Using the gridded datasets, VPD was calculated on a weekly basis by means of the difference between e_s and e_a following Allen et al. (1998), as

$$VPD = e_s - e_a \tag{1}$$

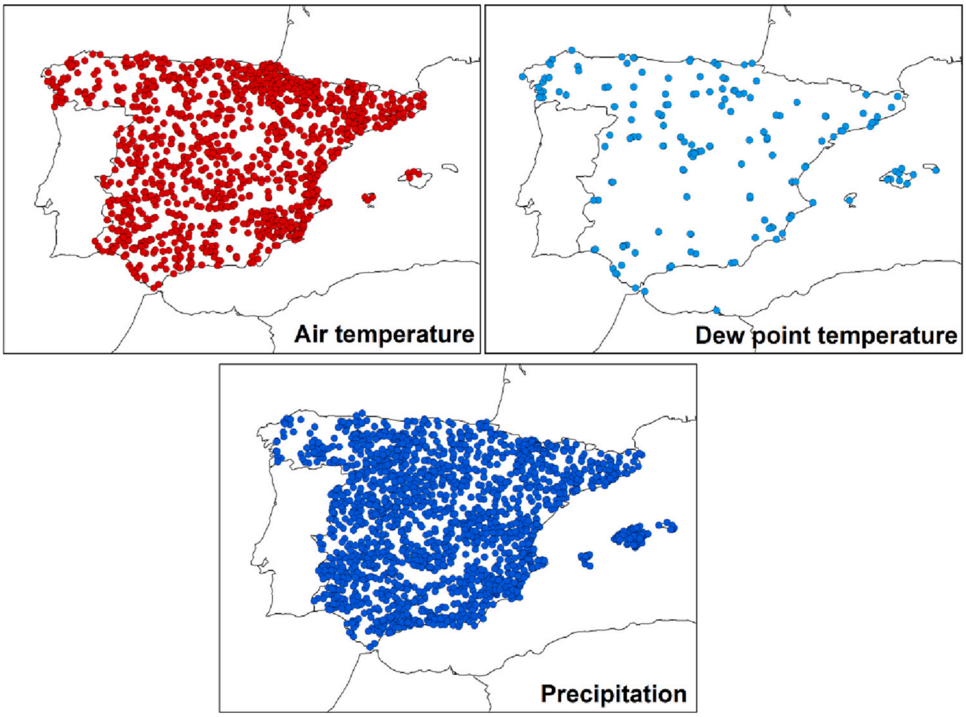

Fig. 1. Spatial distribution of the available meteorological stations for air temperature, dew point temperature and precipitation.

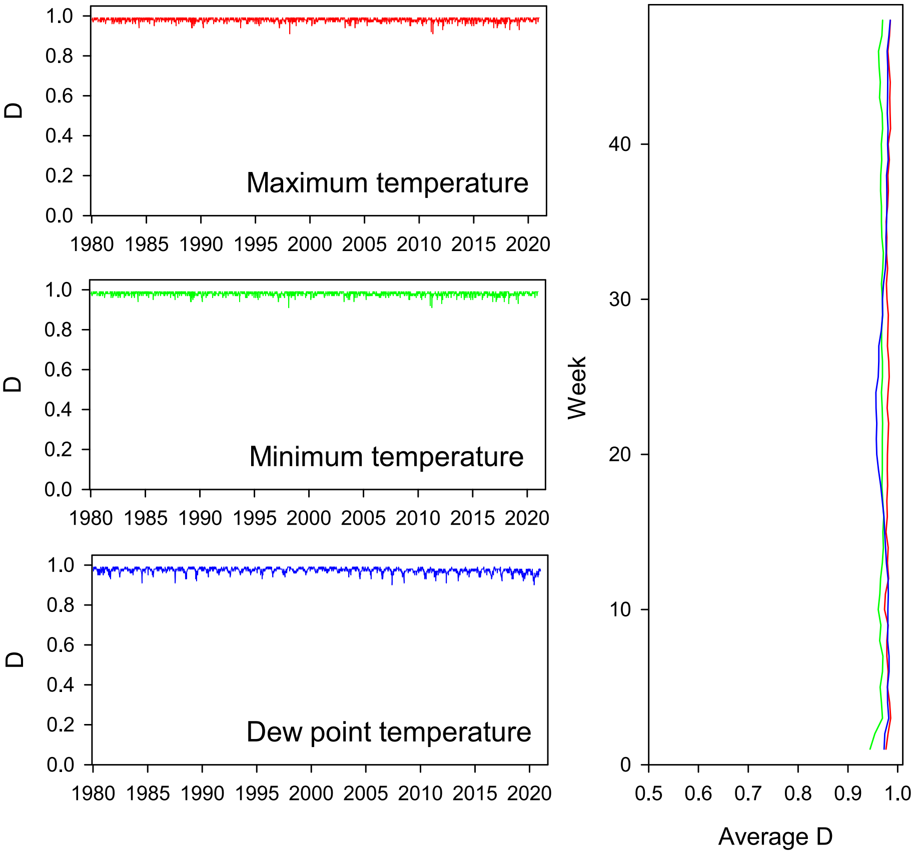

Fig. 2. Validation statistics of the weekly records of maximum and minimum air temperatures and dew point temperature in Spain between 1980 and 2020. Left: evolution of the Wilmot's D statistic each week, Right: Average D values each week of the year.

where e_s is obtained using both maximum (T_{max}) and minimum temperature (T_{min}), as recommended by Allen et al. (1998), via:

$$e_s = \frac{e^o(T_{max}) + e^o(T_{min})}{2} \tag{2}$$

and e_a is obtained using dew point temperature (T_{dew}), as:

$$e_a = e^o(T_{dew}) \tag{3}$$

Finally,

$$e^o(T) = 0.6108exp\left[\frac{17.27T}{T + 237.3}\right] \tag{4}$$

where T (°C) is substituted by T_{max}, T_{min} or T_{dew}.

In Spain, an official network of soil moisture observations is lacking, with only a few short-term measurements, which are very localised over space and maintained by local research teams (Martínez-Fernández and Ceballos, 2003; Scaini et al., 2015; Sillero-Medina et al., 2021). For this reason, we employed modelling data, based on meteorological and remote sensing input data, in order to assess the possible role of soil moisture in VPD variability and trends. Specifically, surface and root zone soil moisture (in m^3/m^3) and E_t (in mm) were obtained on a daily basis from the GLEAM v3.5a dataset (https://www.gleam.eu/) for the period 1980–2020 (Martens et al., 2017; Miralles et al., 2011). GLEAM has been fully validated at the global scale using data of Eddy-covariance towers located on different environment (Martens et al., 2017). Thus, recent comparisons of the output of different model simulations have showed that GLEAM reproduces well the magnitude and temporal variability of the available observations (Guo et al., 2022; Liu et al., 2023; Yang et al., 2022). To match the VPD's temporal resolution, these daily data were aggregated to a weekly time scale. Also, as the spatial resolution of the two datasets is different (i.e. 1 km^2 for T, RH, VPD, and precipitation (P), and 0.25° for the GLEAM data), the VPD and P data were resampled by a bilinear algorithm to match the spatial resolution of the GLEAM dataset. We believe that this spatial resolution is sufficient to characterise the VPD response to different climatic conditions across Spain.

3. Analysis

Trend and variability of VPD were analysed for the whole of Spain between 1980 and 2020. Trends were assessed on a weekly, seasonal, and annual scale, although the majority of analyses were performed on seasonal and annual scales, while weekly data were used for some comparisons. Overall, seasons were defined in a standard way: winter (DJF), spring (MAM), summer (JJA), and autumn (SON). The main analysis was based on the gridded datasets but we also included the analysis in the independent meteorological stations in order to show the observed trends in the locations in which the data is available.

To analyse changes in VPD and other related climatic variables, the nonparametric Mann–Kendall statistic was used. This is a non-parametric test, which quantifies the degree to which a trend is consistently increasing or decreasing. As this statistic is sensitive to the presence of autocorrelation in the time series, we considered a modified version of this test, which returns the corrected p values after accounting for temporal pseudoreplication (Hamed and Ramachandra Rao, 1998; Yue and Wang, 2004). To assess the magnitude of change in the different variables over the study period, we used a linear regression analysis between the series of time (independent variable) and VPD and other variables (dependent variables). The slope of the regression suggested the amount of change (per year), with higher slope values indicating greater change and vice versa. While trends were assessed at the grid level (0.25°), we also explored the whole picture for Spain by creating regional series based on averaging all gridded series for each variable over the entire country. Trends were assessed at the 95% significance level ($p < 0.05$).

We assessed the relationship between the interannual variability of VPD and other variables using Pearson's r correlation coefficient. To remove the possible effect of trends presented in the time series on correlation magnitude and significance, correlations were computed for the detrended series.

To quantify the independent role of precipitation and soil moisture on VPD, we used the partial correlation to the detrended series of the different variables. This is important, recalling that there is a high dependency between VPD and other contributing variables (e.g. precipitation, soil moisture, and air temperature) (Kimm et al., 2020; Lu and Takle, 2010; Scaini et al., 2015; Yuan et al., 2020; Zhao and Khalil, 1993). Partial correlation measures the association between two variables (dependent and independent) after fixing the role of other possible controlling variables (Baba et al., 2004).

3. Results

3.1. *Trends in VPD and its controlling variables*

Fig. 3 illustrates seasonal and annual changes in VPD from 1980 to 2020. Results suggest statistically significant positive trends, mainly in spring, summer, and annually. On the other hand, VPD did not exhibit significant changes in winter and autumn over Spain, implying that VPD increase was mainly assigned to the warm season. A similar temporal pattern was seen for data on a weekly scale, as we noted statistically significant positive trends between weeks #19 (4th of May) and #32 (4th of August), which corresponds to late spring and summertime.

Spatially, we found spatial differences in the magnitude of VPD trends as a function of season (Fig. 4). In summer, the most pronounced increase in VPD was noted in southern and eastern Spain, while weaker changes were recorded in northern Spain. The spatial patterns of annual trends seem to be more related to VPD trends in summer. In contrast, significant trends during winter and autumn were only seen across small areas. The trends based on the gridded dataset show the same spatial and seasonal patterns identified by the independent meteorological stations (Fig. S3). Thus, the majority of the stations with data of dew, maximum and minimum temperature necessary to calculate VPD show positive and statistically significant trends in Spring, Summer and at the Annual scales.

Fig. 5 depicts the seasonal and annual changes in the driving variables of VPD. It can be noted that the strong increase in VPD during the warm season was inconsistent with the observed changes in some variables like soil moisture, evaporation, and precipitation. Notably, no significant changes in both surface and root soil moisture were found over Spain, either seasonally or annually. As illustrated, the temporal evolution of root and surface soil moisture seems to be stationary over the study period, with low interannual variability. For precipitation, a statistically significant increase was noted from 1980 to 2020 on the annual scale, which was less driven by the small changes in spring and autumn. This is confirmed by the coherent relationship between E_t and precipitation trends. Precipitation showed a statistically significant increase from 1980 to 2020 on the annual scale, which is the result of small increases in spring and autumn. This pattern favoured a general increase of E_t, particularly in spring, but not relevant changes in summer E_t. This is simply because, during summer, soils are dominantly dry and precipitation is too low to allow soil recharge, taking into account the high AED recorded during this season. The spatial patterns of VPD and related variables at the grid level were reflected at the country level (Figs. S4-S7). This pattern can be seen in the statistically non-significant trends of the root and surface soil moisture on the annual and seasonal scales across Spain.

Importantly, it can be noted that the observed VPD trends in Spain during the warm season over the past four decades were mostly driven by the radiative forcing associated with anthropogenic climate change. This was evident by the significant temperature rise during the warm season and annually. Fig. 6 illustrates the average annual and seasonal series of minimum and maximum air temperatures and relative

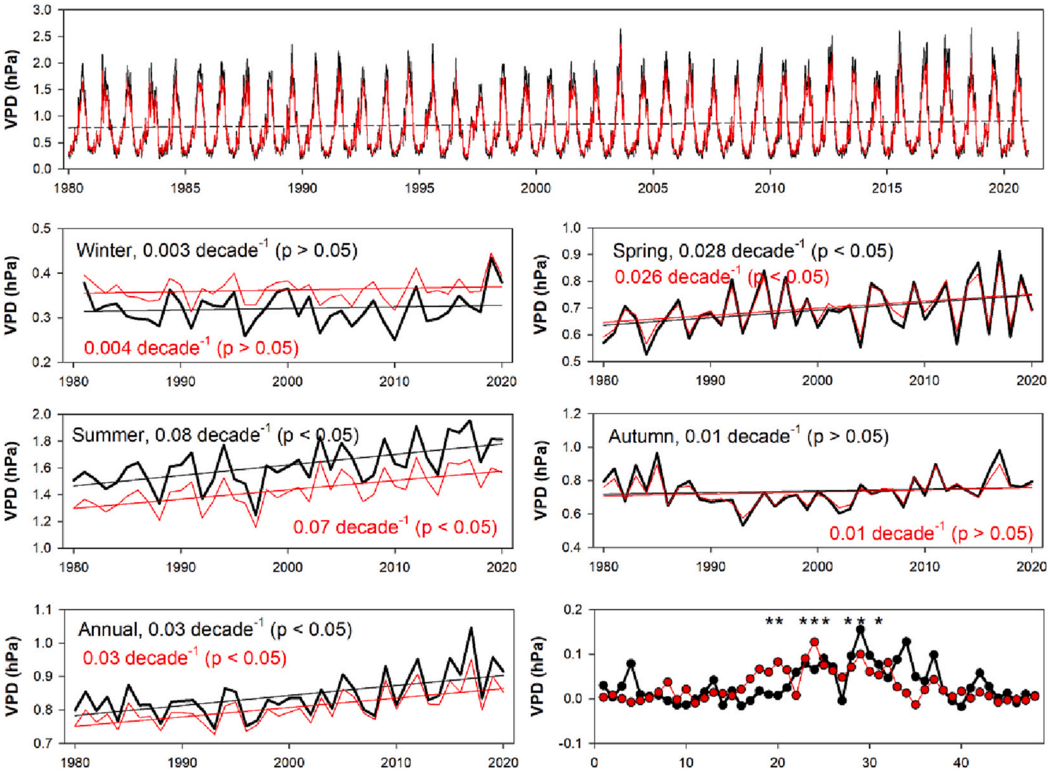

Fig. 3. Evolution of the average VPD for Spain on the annual and seasonal scales. Bottom-right plot provides the magnitude of change and statistical significance of the VPD changes on the weekly scale. Black lines and texts inform on the evolution based on the interpolated gridded dataset. Red lines and texts show the evolution based on the available meteorological stations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

humidity for the whole of Spain between 1980 and 2020. As depicted, both minimum and maximum air temperatures showed significant positive trends in spring, summer, and annually, with less significant changes in winter and autumn. In contrast, relative humidity showed a declining trend in spring and summer, although this trend was statistically significant only during summertime, with a rate of decline of 6.4% on average. Figs. S8-S10 suggest that the patterns identified based on the regional series were spatially coherent with the identified trends of air temperature (increase) and relative humidity (decrease) over large areas of Spain, especially in summer.

3.2. Links between VPD variability and its controlling variables

Fig. 7 summarizes the links between the interannual variability of VPD in Spain and soil moisture and other climate variables. This association was assessed between the annual and seasonal detrended VPD and detrended E_t, root zone, and surface soil moisture. Statistically significant negative correlations between VPD and root and surface soil moisture were found in all seasons and annually. Higher correlation values were found between VPD and surface soil moisture than with root zone soil moisture. For E_t, statistically significant correlations ($p < 0.05$) with VPD were noted only on the annual scale. In all cases, this relationship was negative in all seasons, indicating that VPD tended to be reduced under high E_t and soil moisture. This would be the expected behaviour in the warm season, in which land-atmosphere feedback reaches its maximum in the year given maximum values of radiation at the same time that atmospheric circulation is less intense than in other seasons. Nevertheless, although the negative relationship between VPD and E_t and soil moisture could be expected in the summer season, the statistically significant and strong relationship recorded in winter, spring, and autumn between VPD and soil moisture is not easily explained by the land-atmosphere feedbacks, as these processes are not relevant during these seasons. Unexpectedly, recalling this negative association, we found that the spatial patterns of correlations between VPD and E_t, surface and root zone soil moisture were almost consistent, irrespective of season, even with much stronger correlations in cold seasons (e.g. autumn) than in warm seasons (e.g. summer) (Figs. S11-S13). Interestingly, the relationship between the interannual variability of VPD and precipitation was almost similar to that of soil moisture, with negative correlations in all seasons and annually (Fig. 8). Spatially, Fig. S14 shows that the negative correlations between VPD and rainfall were high and statistically significant in large parts of Spain in all seasons and all years.

Surface soil moisture and precipitation are strongly related (Figs. S15-S16). Nonetheless, VPD showed a higher partial correlation with soil moisture than with precipitation on the annual scale and in autumn. Rather, this correlation was higher with precipitation in winter and spring. In summer, the correlation values between VPD and soil moisture and precipitation were almost similar (Table S1 and Figs. S17-S18). Thus, the ultimate physical mechanisms that largely control VPD's interannual variability are difficult to ascertain. The dominant physical driver cannot be determined using a partial correlation statistic. Nevertheless, due to their strong correlations, soil moisture and precipitation can be seen as providing roughly the same information. Nevertheless, we hypothesize that the relationship between VPD and soil moisture is non-direct and fundamentally caused by the role of precipitation on VPD. This hypothesis is based on the stronger negative correlations found considering surface soil moisture rather than those obtained using Et and root soil moisture. Also, our hypothesis is supported by the fact that these correlations were similar to those obtained with precipitation. The role of precipitation in VPD variability can also be seen in the context of the relationship between precipitation and both temperature and relative humidity, combined with the significant impact of precipitation on soil moisture variability.

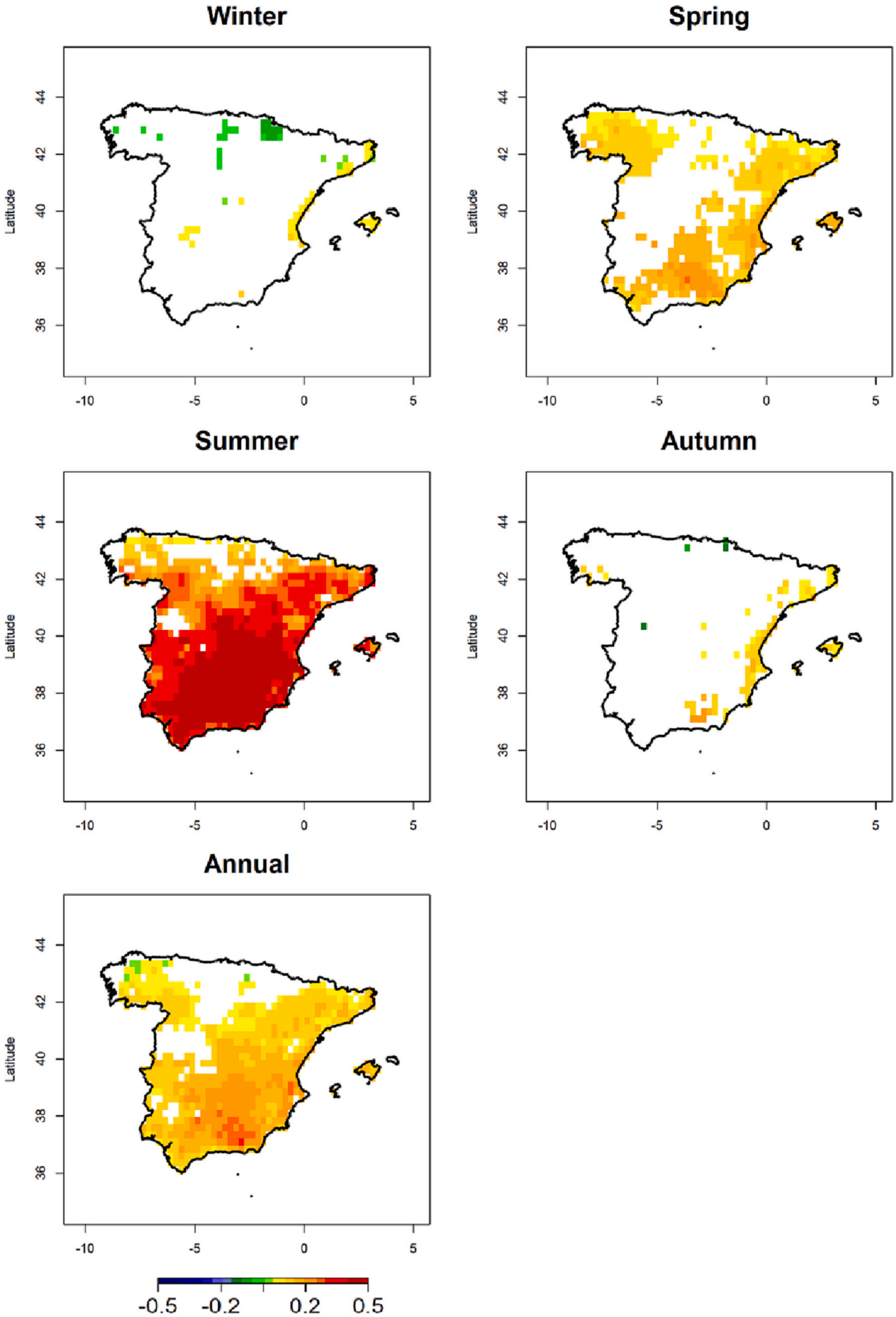

Fig. 4. Spatial distribution of the magnitude of the trend in VPD (hPa) between 1980 and 2020 on the seasonal and annual scales. White areas correspond to regions with no significant trends.

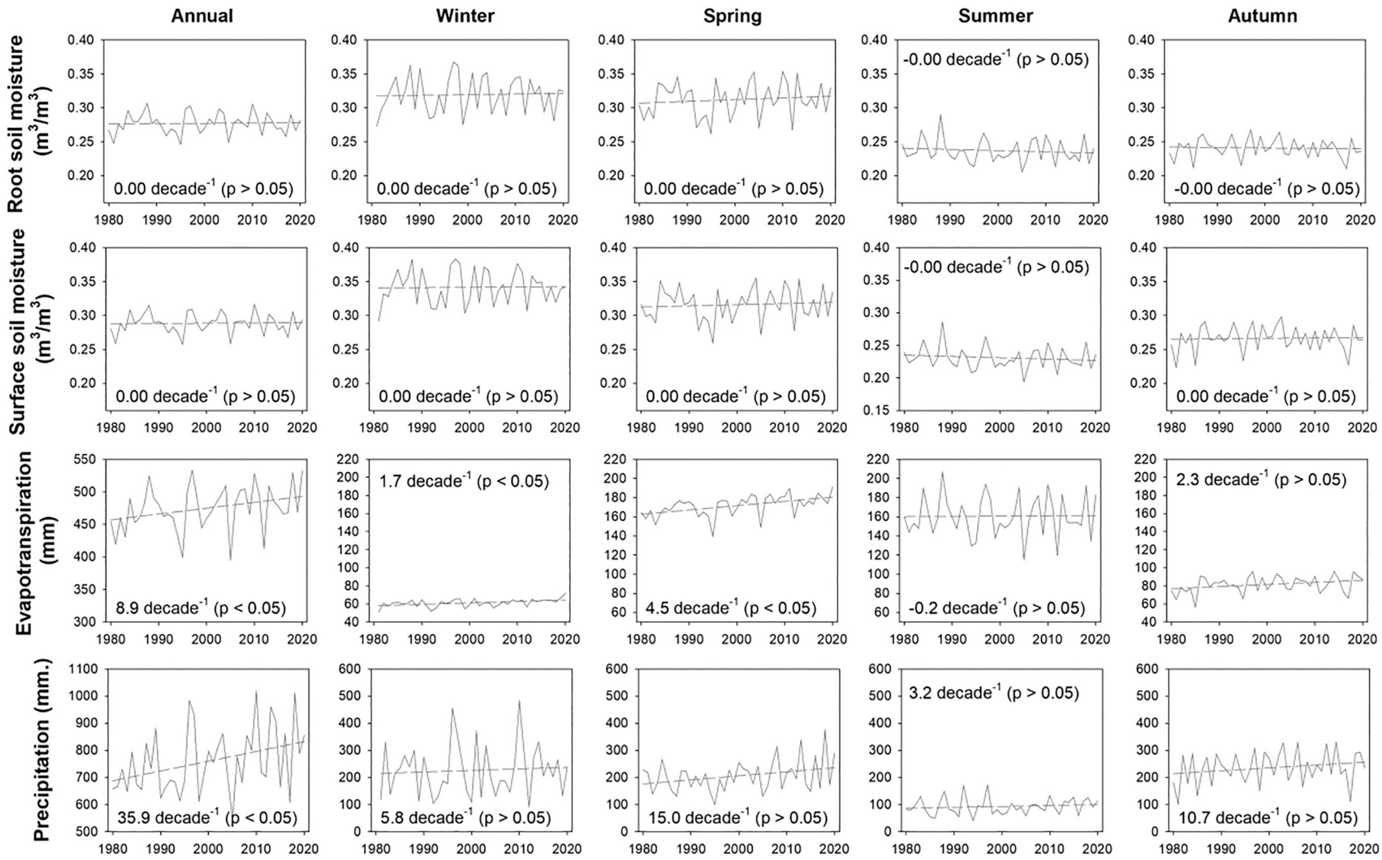

Fig. 5. Annual and seasonal evolution of root and surface soil moisture, evapotranspiration, and precipitation over the whole Spain for the period 1980–2020.

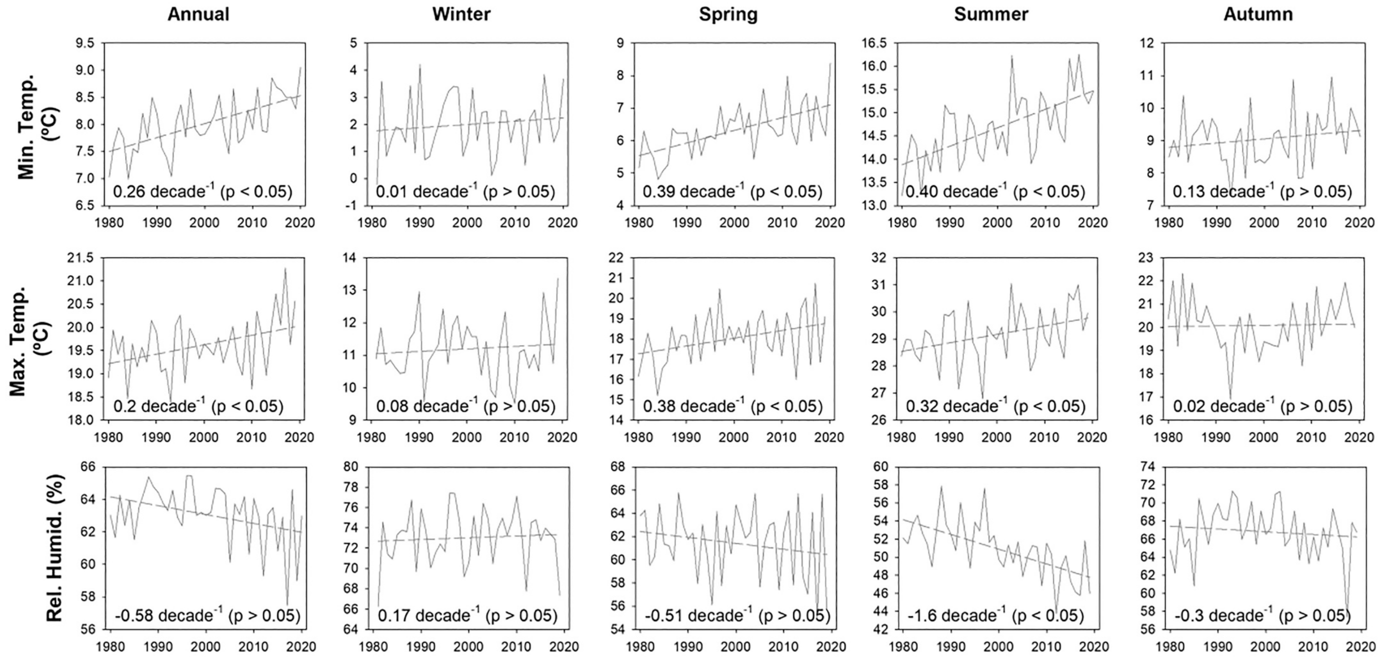

Fig. 6. Annual and seasonal evolution of minimum and maximum temperatures and relative humidity over the whole Spain for the period 1980–2020.

In order to investigate in more depth the possible dominant mechanisms controlling interannual variability of VPD, we analysed the correlations between VPD and both soil moisture and precipitation using weekly data. For the regional series, results suggest lower correlations between root zone soil moisture and VPD than between surface soil moisture and VPD. This finding was evident for the different weeks of the year (Fig. 9), and particularly in summer. From February to September, the correlations between the interannual variability of VPD and precipitation were stronger than the correlation between VPD and surface soil moisture. Expectedly, the correlation between VPD and soil

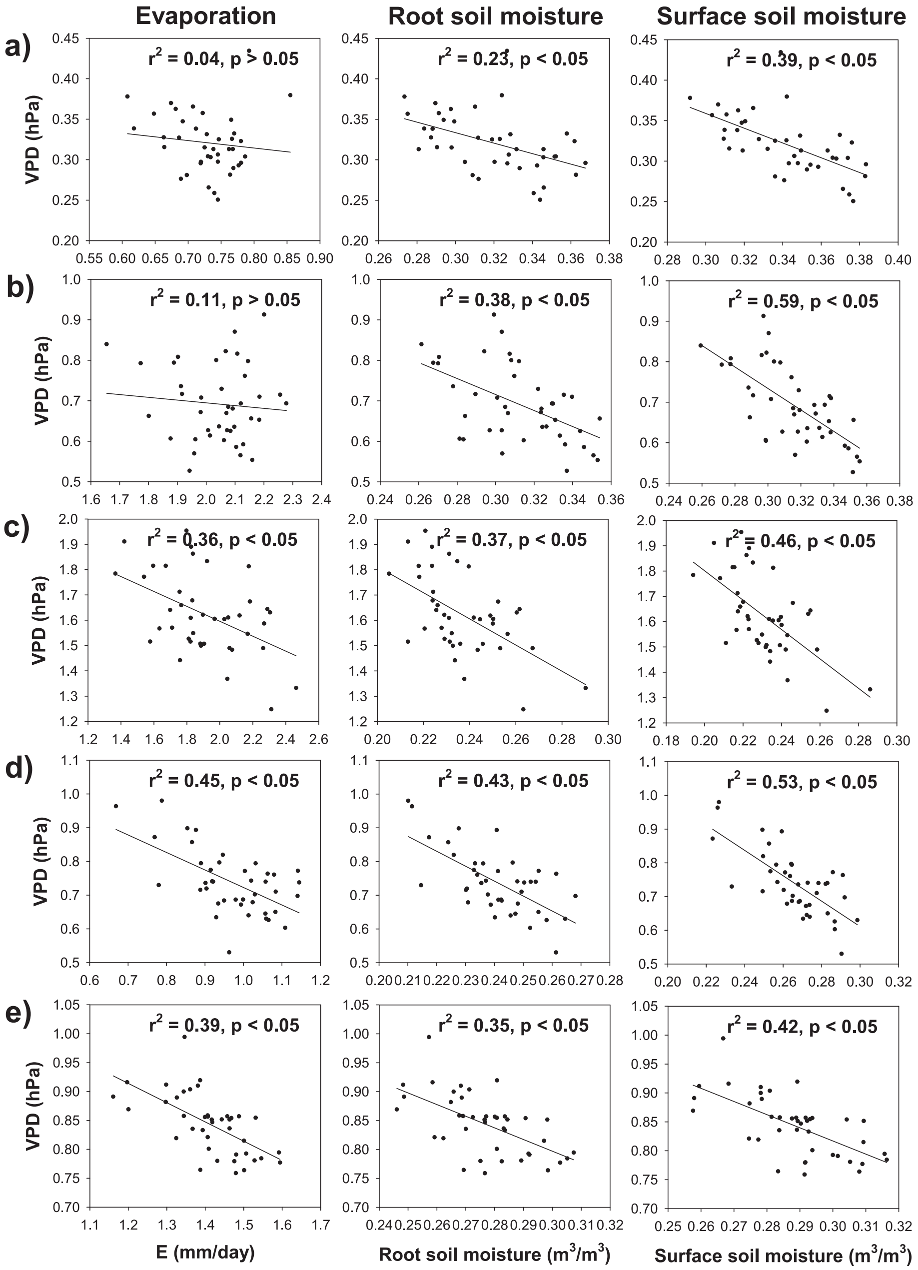

Fig. 7. Relationships between detrended regional series of VPD and evapotranspiration$_t$, root and surface soil moisture on the seasonal and annual scales. a) winter, b) spring, c) summer, d) autumn, and e) annual.

moisture was markedly weak between October and December. The spatial patterns of correlations with VPD were similar during the different weeks of the year considering surface soil moisture and precipitation (Figs. S19-S20). Notably, during the warm season (weeks 23–34), the correlations between VPD and soil moisture were weak across the whole of Spain, in a period in which soil is normally dry and in which precipitation is low and spatially sparse.

Since variations of VPD during summer were not clearly connected with the variability of either precipitation or soil moisture, we assessed the connection of the direct driving variables of VDP variability (i.e. air temperature and relative humidity) with soil moisture and precipitation (Figs. S21 and S22). We noted that both precipitation and soil moisture exhibited similar associations with maximum air temperature and relative humidity across all seasons. Thus, we did not find a strong coupling between soil moisture variations and air temperature and relative humidity during summer, or a different influence than that directly hinted by precipitation.

On the weekly scale, correlations between VPD and both maximum air temperature and relative humidity were almost similar (Fig. S23). The patterns of correlations in the 48 weeks of the year indicated that VPD was strongly associated with air temperature variability during warm periods of the year (spring, summer, and early autumn), during which the impacts of relative humidity become more stable. The weekly correlations between maximum air temperature and surface soil moisture were similar in magnitude and temporal pattern to those of maximum air temperature and precipitation. Also, the correlations between these two variables and relative humidity were similar, but the correlations were slightly higher during summertime when considering precipitation than surface soil moisture.

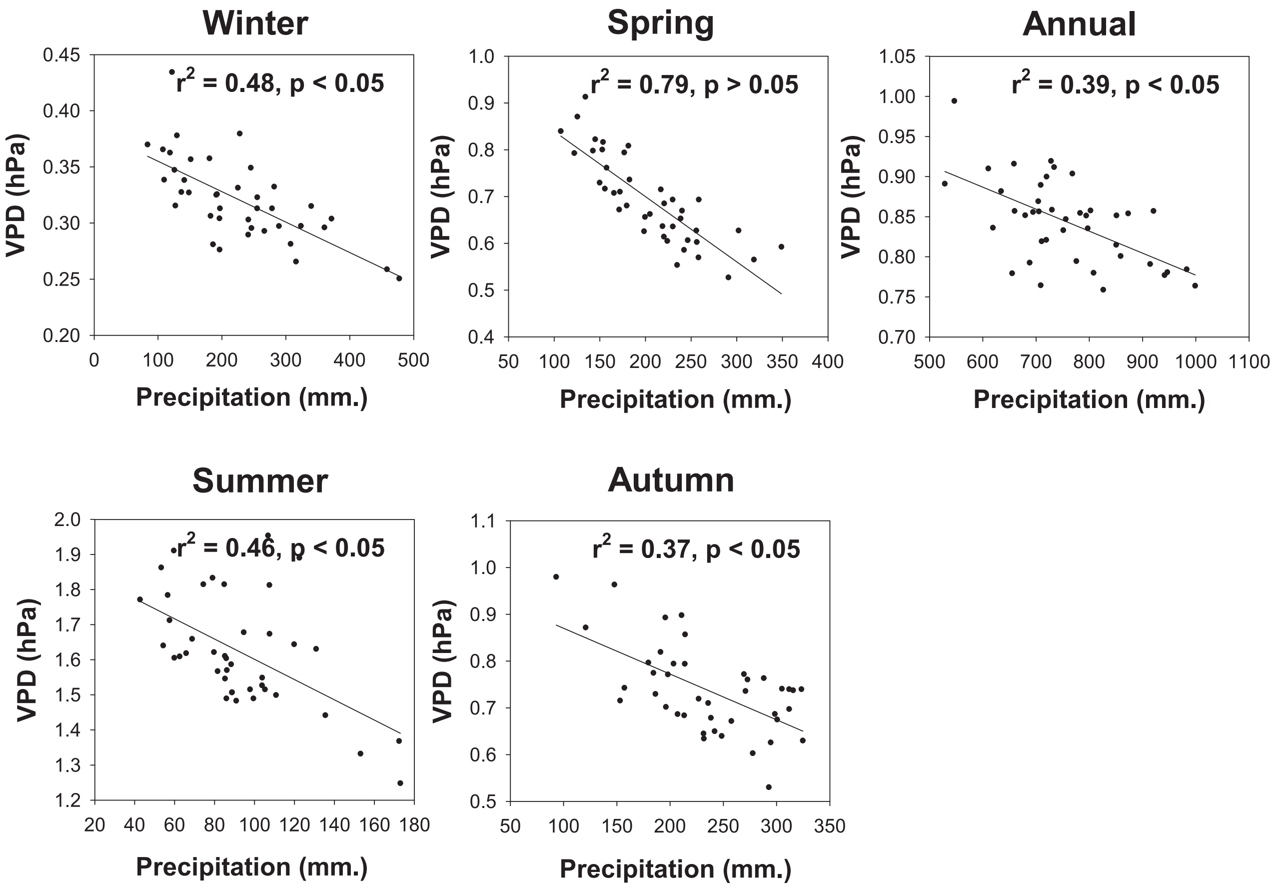

Fig. 8. Relationships between detrended regional series for VPD and precipitation on the seasonal and annual scales.

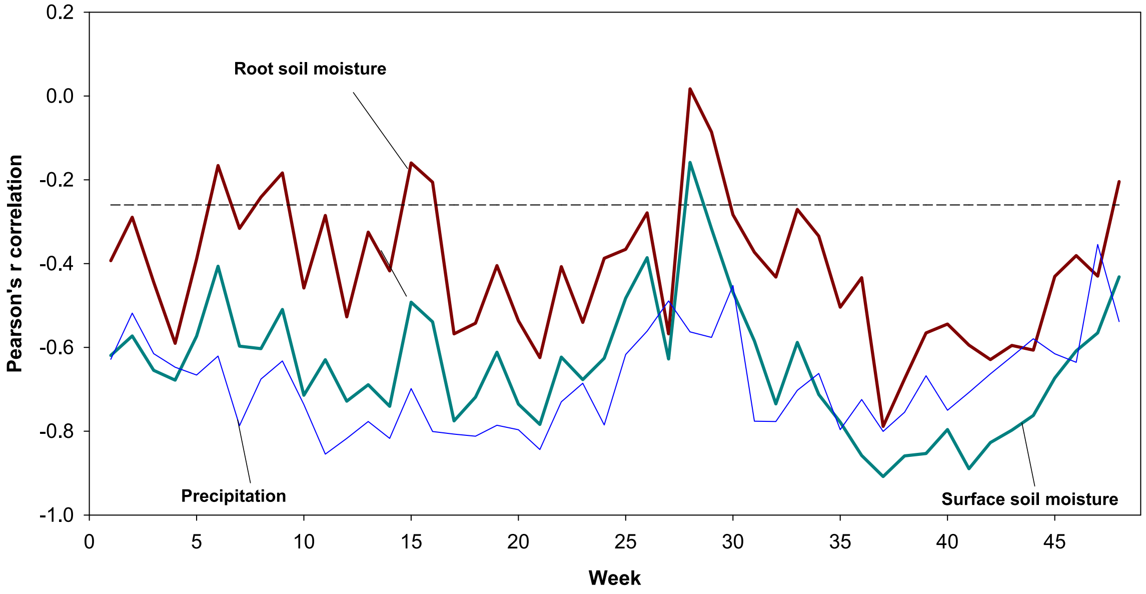

Fig. 9. Correlations between the regional weekly series of VPD and those of precipitation, root, and surface soil moisture. Dashed line represents the limit of statistically significant correlations.

4. Discussion

This study analysed recent temporal variability and trends in VPD across Spain between 1980 and 2020 and their connection with soil moisture and different climate variables, including precipitation (P), air temperature (T), and relative humidity (RH). These assessments were made on different timescales, varying from weekly, seasonal, and annual. We employed a high-quality updated VPD dataset that has been fully validated and compared with independent precipitation and soil moisture data. VPD data is fully independent of the data of the land variables, such as E_t and soil moisture. Also, it is assured that the relationships between VPD, precipitation, evapotranspiration, and soil moisture were not affected by the characteristics of mechanistic models, which were used to obtain soil moisture simulations that are coupled with inputs of VPD and P. This issue is very critical since the role of soil moisture in evapotranspiration evolution and, thereby, VPD could be affected in some way by how land-atmosphere coupling is included in the modelling scheme (Materia et al., 2022; Stegehuis et al., 2013). Thus, strong land-atmosphere feedback in models usually causes an underestimation of the sensitivity of E_t to VPD and, conversely, an overestimation of the sensitivity to low soil moisture (Liu et al., 2020b).

One caveat related to this study is the lack of soil moisture observations in Spain, which guided our decision to rely on soil moisture data derived from a model that combines both observational and remote sensing data (Martens et al., 2017). However, even though there is some uncertainty in the modelled data, it has been shown to be of good quality when compared to observations in different parts of the world (Beck et al., 2021).

4.1. *Trends in VPD*

Results suggest a dominant increase in VPD in Spain over the last four decades, which is consistent with the trends assessed based on different observations and reanalysis datasets on a global scale (Lian et al., 2020; Weedon et al., 2011). In this study, the increase in VPD was more pronounced during the warm season, explaining the relevant VPD increase observed on the annual scale.

Also, this work attempted to explain the strong observed trend and variability of VPD in recent decades through examining their connection with some relevant variables such as P, E_t, and soil moisture. Amongst them, soil moisture has been proven as a key controller of VPD variability in several recent studies. For example, Stegehuis et al. (2021) suggested the role of soil moisture drying at the beginning of summer in explaining summer warming in some areas of western Europe, including parts of central Spain. In the same context, this mechanism is likely to have a significant impact on trends of summer maximum T under future climate change scenarios characterized by enhanced anthropogenic emissions (Vogel et al., 2017). As opposed to these findings, our study demonstrates that the increase in VPD over the past decades does not concur with changes in either soil moisture (both surface and root) or E_t. Specifically, soil moisture at the surface and the root levels was almost stationary on the seasonal and annual scales, with non-significant changes between 1980 and 2020. While earlier studies in the Mediterranean indicated a decline in soil moisture in the region, including Spain, during the dry season due to increased evapotranspiration (e.g., Padrón et al., 2020), this trend was not confirmed for the soil moisture dataset used in Spain over the period 1980–2020. Our findings suggest a significant increase in E_t during winter, spring, and annually, with fewer changes in summer. These results may stress the possible role of the intensity of water flow from land to the atmosphere that may control T, RH, and VPD trends. Thus, the increase in E_t may be linked directly to the observed increase in P, which was noted on the annual scale during the study period. A similar pattern was noted in most of Southern Europe during the last four decades (Gutiérrez et al., 2021). As AED is extremely high in Spain (Tomas-Burguera et al., 2020), E_t tended to be controlled more by P than by AED, particularly in the dry areas of Spain (Beguería et al., 2014), which are dominant in the country.

The amount of irrigated land in Spain has grown a lot (Pinilla, 2006), from 1.45 million of hectares in 1950 to 3.83 million of hectares in 2020, and this growth was seen as a major cause of the sharp drop in streamflow in Spain (Lorenzo-Lacruz et al., 2012; Vicente-Serrano et al., 2019), mostly because crops are losing more water through enhanced evapotranspiration (Jiménez-Aguirre and Isidoro, 2018). Nonetheless, it seems that the increase in irrigated lands, and thereby, crop evapotranspiration did not correspond to a reduction of summer T and VPD. Again, this finding contradicts some earlier regional studies. A representative example is Ambika and Mishra (2020) who found that the decreased VPD in India since 2000 was associated with increased soil moisture, E_t, and RH due to increased irrigated surface.

Soil humidity is generally low in most of Spain during summer. This is caused by the low P and high E_t from dominant crops in spring and active vegetation in summer, which deplete soil moisture (Austin et al., 1998). The exceptions correspond mainly to humid regions in the north, which showed statistically significant positive trends in E_t and negative trends in soil moisture. This pattern could explain the increasing water stress in forest areas in some humid regions of Spain (Camarero et al., 2015; Carnicer et al., 2011; Sánchez-Salguero et al., 2017). In these humid regions of Spain, it is expected that the enhancement of E_t would be coherent with the general AED increase recorded in the region (Tomas-Burguera et al., 2020). Nevertheless, in the rest of the country, summer soil moisture is extremely low, with less interannual variability. As such, soil dryness is not expected to increase more due to the observed increase in AED.

The evolution of VPD, which is independent of soil moisture trends, suggests that the main mechanisms explaining long-term VPD trends are related to the radiative effects caused by anthropogenic climate change. VPD did not show an increase in winter and autumn, which is in agreement with the stationary behaviour of T and RH in these seasons. In contrast, in spring and summer, there was an important VPD increase, which was driven by a strong increase in T and a decrease in RH, which are particularly strong in summer. The increase in T seems to be clearly connected with global warming processes, which have been significant during the last decades over the whole Mediterranean region (Doblas-Reyes et al., 2021). In the absence of soil moisture changes in Spain over the last four decades, anthropogenic forcing seems to be the most reasonable explanation of the strong increase of VPD, with a secondary role of possible land-atmosphere feedbacks.

Our results suggest a strong decrease in RH over the past decades, which agrees with several other mid-latitudinal areas of the northern hemisphere (Vicente-Serrano et al., 2018). Given the stationary behaviour of soil moisture and evapotranspiration, the strong decrease in RH can be seen in the context of the differential warming rates between oceanic and continental areas (Byrne and O'Gorman, 2013, 2018), which can lead to sub-saturation conditions in continental areas (Sherwood and Fu, 2014). Most of Spain is subjected to atmospheric moisture with an oceanic origin (Gimeno et al., 2010). Accordingly, increased T in land areas seems to contribute to a general decrease in RH, enhancing positive VPD trends.

4.2. *Drivers of temporal variability of VPD*

This study indicates a strong interannual variability of VPD in the last four decades. To attribute this variability, changes in VPD were linked to the variability of E_t, soil moisture, and P. We found a negative and significant correlation between VPD, E_t, and soil moisture on both the annual and seasonal scales. This negative association could suggest that possible coupling processes between soil and the atmosphere may play a fundamental role in driving the interannual variability of VPD in Spain. Land-atmosphere coupling has been suggested as a key driver of VPD variability in most world regions when considering the role of soil moisture (Liu et al., 2020a; Zhou et al., 2019). Atmospheric dynamics plays an important role in driving variables of VPD, which should also be taken into consideration. The following paragraphs will attempt to distinguish between results that support the importance of land-atmosphere coupling and those that suggest the importance of atmospheric dynamics.

Thus, there are some aspects that prevent the direct association of land-atmosphere coupling and VPD. First, the possible land-atmosphere feedbacks controlling VPD variability are not expected in seasons different to summer since air advection is dominant. Although some studies have suggested a land-atmosphere coupling based on a negative and significant correlation between soil moisture and VPD on the annual scale (Liu et al., 2020a), this correlation obtained for the long-term could mix different physical processes. For example, air advection is dominant during the humid season and feedback between the surface and the atmosphere would not be expected. Thus, we consider that the relationship between soil moisture and VPD in the humid season would be basically connected to the control of soil moisture by P. Thus, it is much more plausible that variability of P is the real driver of VPD rather than soil moisture. This is simply because P is strongly coupled with RH (Kimm et al., 2020; Lu and Takle, 2010) and is also highly correlated with T (Alder et al., 2008; Trenberth and Shea, 2005; Zhao and Khalil, 1993). In Spain, during the cold and humid seasons, soil moisture is fundamentally determined by P given the low T and thereby the absence of evapotranspiration (Austin et al., 1998). Therefore, the negative correlation between soil moisture and VPD in large areas of Spain in winter, spring, and autumn would not be suggestive of a control of the VPD by soil moisture as a consequence of the influence of land humidity. Rather, soil moisture variability is simply affected by P variability, which is ultimately determined by atmospheric dynamics (Paredes et al., 2006; Rodriguez-Puebla et al., 1998).

The second issue that hinders a direct attribution of VPD variability to variations of soil moisture is the fact that surface soil moisture showed higher correlations with VPD than both root zone soil moisture and E_t. Considering that >70% of E_t is in the form of plant transpiration (Jasechko et al., 2013) and that water is obtained from plants in root layers, stronger correlations between VPD and root soil moisture than those with surface soil moisture would be expected, and even higher correlation between VPD and evapotranspiration, since evapotranspiration is a better proxy of the latent heat flux to the atmosphere. In Spain, we found that correlations were higher between VPD and surface soil moisture in all seasons and annually. Thus, a higher correlation with surface soil moisture was also found in summer, in which surface soil is extremely dry, with less interannual variations.

In light of these findings, it is still not recommended to claim that interannual variations in land-atmosphere feedback caused by interannual variability in soil moisture may be the primary driver of VPD in Spain during summer season. Thus, we showed that, during summertime, correlations between soil moisture and VPD decreased more on the weekly scale. Some studies suggest that the coupling between soil moisture and VPD depends largely on the time scale of analysis (Novick et al., 2016; Teuling et al., 2006). For example, long-time scales (e.g. annual and seasonal) showed stronger coupling than hourly, daily, and weekly time scales (Kimm et al., 2020; Sulman et al., 2016). Here, we showed that, on the weekly scale, the relationship between surface soil moisture and VPD was negative and statistically significant during most of the year, although correlations decreased during summer weeks (between June and August). A similar pattern was observed with P, but the decline in the correlation was lower. These results do not imply that changes in land-atmospheric feedbacks, caused by variations in soil moisture, may not affect VPD. However, the statistical analysis makes it difficult to separate this effect from the effect caused by P variability on T and RH and the strong effect of atmospheric mechanisms (as south warm advections, Sousa et al., 2019), together with the role of water transport from the surrounding Mediterranean sea, which is the principal source of atmospheric moisture on P in Spain during summer (Gimeno et al., 2010).

In Spain, soil moisture effects on T and VPD may be restricted to particular conditions, such as extreme heat waves. This has been the case in different regions worldwide (Fischer et al., 2007; Hirschi et al., 2011; McKinnon et al., 2021; Miralles et al., 2014). Thus, it is expected that its effect may be characterized by non-linear characteristics (Song et al., 2020; Vargas Zeppetello et al., 2019). Under humid conditions, E_t is not limited (Seneviratne et al., 2010), so it would not control VPD. Nevertheless, under extremely dry conditions, the variability of soil moisture is low and, accordingly, changes in Et are not expected to occur or control VPD (Chen et al., 2014). In such cases, VPD would be strongly affected by air advections (Stocker et al., 2018). Thus, atmospheric mechanisms may strongly affect land-atmosphere feedbacks during summer, considering dry soils (Gu et al., 2006). For example, Ford et al. (2015) analysed the connection between synoptic patterns and soil moisture-atmosphere feedbacks that control convection in the central US, demonstrating that unorganized convection was mostly related to 500 hPa ridging, which caused increased VPD over very dry soils. On the other hand, under other atmospheric conditions, the variations of VPD were reduced. Stocker et al. (2018) suggested that the main control of soil moisture on VPD during summer months would be recorded in intermediate conditions. Nonetheless, due to the predominant dry soils in Spain during summertime, these conditions are uncommon. This nonlinear relationship could explain the low correlations found between soil moisture and VPD in summer since the interannual variability of soil moisture is low and it would not cause substantial modifications in the interannual variations of the land-atmosphere feedbacks that may affect VPD.

Another possible contribution to the general decoupling between soil moisture variations and VPD in Spain during summer can be the response of plants to high values of VPD that are recorded in this season. Average T in Spain in summer is high (Martin-Vide and Olcina-Cantos, 2001) and the occurrence of heat waves with T above 35 °C caused by air advections is very frequent (Olcina, 1994). Under these conditions and in order to reduce evapotranspiration, plants reduce the stomatal conductance (Grossiord et al., 2020), which could finally decouple soil-atmosphere interactions.

Therefore, the strong control of the land-atmospheric coupling under climate change conditions during summertime, as suggested for central and Western Europe (Seneviratne et al., 2006), is not evident in southwestern Europe. This may be attributed to the dominant dry conditions recorded every year, and also the physiological plant strategies to cope with water stress. This does not mean that soil moisture may contribute to the severity of heat waves and droughts, as suggested by some recent studies (Ribeiro et al., 2020; Russo et al., 2019), but its role in determining the interannual variability of VPD, even in summer season, seems to be limited.

5. Conclusions

This study suggests a significant increase in the VPD over Spain in the last four decades. These changes were more pronounced during the warm season and annually. Results demonstrate that this increase was independent of the evolution of E_t, soil moisture, and P. Rather, they were mostly related to the different radiative effects related to anthropogenic climate change. Moreover, the interannual variability of VPD seems not to be coupled with the variations of soil moisture during summer season: a finding that contradicts with findings from global studies that suggested strong coupling between soil moisture and VPD, including Spain, on the seasonal and annual scales. Temporal variability of VPD in the cold season would be mostly related to the mechanisms of climate variability that control temperature and humidity variations and that are basically linked to atmospheric mechanisms. In summers, the dominant dry soils and possibly physiological plant mechanisms would cause a dominant uncoupling between soil moisture and VPD. For this reason, VPD is probably related to atmospheric mechanisms that control temperature and relative humidity in the region, including warm advections and humidity transport. As increased VPD has important consequences on plant physiology and it strongly determines plant productivity and carbon uptake (Breshears et al., 2013; Grossiord et al., 2020), and since different studies have stressed its role on crops and natural ecosystems (Fu et al., 2022; Lobell et al., 2011; Novick et al., 2016), assessment of VPD variability and trends and their driving physical mechanisms, based on robust databases, seems to be a priority in semiarid and sub-humid regions of the world, where enhanced AED may increase water stress and reinforce climate aridity and the severity of drought events in future climate change scenarios (Vicente-Serrano et al., 2020).

CRediT authorship contribution statement

I. Noguera: Conceptualization, Data curation, Writing – original draft. **S.M. Vicente-Serrano:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Writing – original draft. **D. Peña-Angulo:** Resources, Software, Writing – review & editing. **F. Domínguez-Castro:** Formal analysis, Funding acquisition, Investigation, Methodology. **C. Juez:** Validation, Visualization, Writing – review & editing. **M. Tomás-Burguera:** Conceptualization, Visualization, Writing – review & editing. **J. Lorenzo-Lacruz:** Conceptualization, Visualization, Writing – review & editing. **C. Azorin-Molina:** Conceptualization, Visualization, Writing – review & editing. **A. Halifa-Marín:** Conceptualization, Visualization, Writing – review & editing. **B. Fernández-Duque:** Conceptualization, Visualization, Writing – review & editing. **A. El Kenawy:** Conceptualization, Visualization, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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References

Alder, R.F., Gu, G., Wang, J.-J., Huffman, G.J., Curtis, S., Bolvin, D., 2008. Relationships between global precipitation and surface temperature on interannual and longer timescales (1979-2006). J. Geophys. Res. Atmos. 113 https://doi.org/10.1029/2008JD010536.

Alexandersson, H., 1986. A homogeneity test applied to precipitation data. J. Climatol. 6, 661–675. https://doi.org/10.1002/joc.3370060607.

Allen, R., Pereira, L., Raes, D., Smith, M., 1998. Crop Evapotranspiration : Guidelines for Computing Crop Water Requirements. Food and Agriculture Organization of the United Nations.

Ambika, A.K., Mishra, V., 2020. Substantial decline in atmospheric aridity due to irrigation in India. Environ. Res. Lett. 15, 124060 https://doi.org/10.1088/1748-9326/abc8bc.

Austin, R.B., Cantero-Martínez, C., Arrúe, J.L., Playán, E., Cano-Marcellán, P., 1998. Yield-rainfall relationships in cereal cropping systems in the Ebro river valley of Spain. Eur. J. Agron. 8, 239–248. https://doi.org/10.1016/S1161-0301(97)00063-4.

Baba, K., Shibata, R., Sibuya, M., 2004. Partial correlation and conditional correlation as measures of conditional independence. Aust. N. Z. J. Stat. 46, 657–664. https://doi.org/10.1111/j.1467-842X.2004.00360.x.

Balch, J.K., Abatzoglou, J.T., Joseph, M.B., Koontz, M.J., Mahood, A.L., McGlinchy, J., Cattau, M.E., Williams, A.P., 2022. Warming weakens the night-time barrier to global fire. Nature 602, 442–448. https://doi.org/10.1038/s41586-021-04325-1.

Beck, H.E., Pan, M., Miralles, D.G., Reichle, R.H., Dorigo, W.A., Hahn, S., Sheffield, J., Karthikeyan, L., Balsamo, G., Parinussa, R.M., van Dijk, A.I.J.M., Du, J., Kimball, J.S., Vergopolan, N., Wood, E.F., 2021. Evaluation of 18 satellite- and model-based soil moisture products using in situ measurements from 826 sensors. Hydrol. Earth Syst. Sci. 25, 17–40. https://doi.org/10.5194/hess-25-17-2021.

Beguería, S., Vicente-Serrano, S.M., Reig, F., Latorre, B., 2014. Standardized precipitation evapotranspiration index (SPEI) revisited: Parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. Int. J. Climatol. 34 https://doi.org/10.1002/joc.3887.

Bouchet, R.J., 1963. Evapotranspiration reelle et potentielle, signification climatique. IAHS Publ. 62, 134–142.

Breshears, D.D., Adams, H.D., Eamus, D., Mcdowell, N.G., Law, D.J., Will, R.E., Williams, A.P., Zou, C.B., 2013. The critical amplifying role of increasing atmospheric moisture demand on tree mortality and associated regional die-off. Front. Plant Sci. 4 https://doi.org/10.3389/fpls.2013.00266.

Brutsaert, W., Parlange, M.B., 1998. Hydrologic cycle explains the evaporation paradox [8]. Nature 396, 30. https://doi.org/10.1038/23845.

Byrne, M., O'Gorman, P., 2013. Link between land-ocean warming contrast and surface relative humidities in simulations with coupled climate models. Geophys. Res. Lett. 40, 5223–5227. https://doi.org/10.1002/grl.50971.

Byrne, M.P., O'Gorman, P.A., 2018. Trends in continental temperature and humidity directly linked to ocean warming. Proc. Natl. Acad. Sci. U. S. A. 115, 4863–4868. https://doi.org/10.1073/pnas.1722312115.

Camarero, J.J., Gazol, A., Sangüesa-Barreda, G., Oliva, J., Vicente-Serrano, S.M., 2015. To die or not to die: early warnings of tree dieback in response to a severe drought. J. Ecol. 103 https://doi.org/10.1111/1365-2745.12295.

Carnicer, J., Coll, M., Ninyerola, M., Pons, X., Sánchez, G., Peñuelas, J., 2011. Widespread crown condition decline, food web disruption, and amplified tree mortality with increased climate change-type drought. Proc. Natl. Acad. Sci. U. S. A. 108, 1474–1478. https://doi.org/10.1073/pnas.1010070108.

Chen, D., Wang, Y., Liu, S., Wei, X., Wang, X., 2014. Response of relative sap flow to meteorological factors under different soil moisture conditions in rainfed jujube (Ziziphus jujuba Mill.) plantations in semiarid Northwest China. Agric. Water Manag. 136, 23–33. https://doi.org/10.1016/j.agwat.2014.01.001.

Dai, A., Zhao, T., Chen, J., 2018. Climate change and drought: a precipitation and evaporation perspective. Curr. Clim. Chang. Rep. 4, 301–312. https://doi.org/10.1007/s40641-018-0101-6.

Doblas-Reyes, F.J., Sörensson, A.A., Almazroui, M., Dosio, A., Gutowski, W.J., Haarsma, R., Hamdi, R., Hewitson, B., Kwon, W.-T., Lamptey, B.L., Maraun, D., Stephenson, T.S., Takayabu, I., Terray, L., Turner, A., Zuo, Z., 2021. Linking global to regional climate change. In: MassonDelmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, K. Leitzell, Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R. (Eds.), Climate Change 2021: The Physical Science Basis. Contribution Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Douville, H., Raghavan, K., Renwick, J., 2021. Water cycle changes. In: Climate Change 2021: The Physical Climate, Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

Eamus, D., Boulain, N., Cleverly, J., Breshears, D.D., 2013. Global change-type drought-induced tree mortality: Vapor pressure deficit is more important than temperature per se in causing decline in tree health. Ecol. Evol. 3, 2711–2729. https://doi.org/10.1002/ece3.664.

Fischer, E.M., Seneviratne, S.I., Vidale, P.L., Lüthi, D., Schär, C., 2007. Soil moisture-atmosphere interactions during the 2003 European summer heat wave. J. Clim. 20, 5081–5099. https://doi.org/10.1175/JCLI4288.1.

Ford, T.W., Quiring, S.M., Frauenfeld, O.W., Rapp, A.D., 2015. Synoptic conditions related to soil moisture-atmosphere interactions and unorganized convection in Oklahoma. J. Geophys. Res. Atmos. 120 https://doi.org/10.1002/2015JD023975, 11,511-519,535.

Friedrich, K., Grossman, R.L., Huntington, J., Blanken, P.D., Lenters, J., Holman, K.D., Gochis, D., Livneh, B., Prairie, J., Skeie, E., Healey, N.C., Dahm, K., Pearson, C., Finnessey, T., Hook, S.J., KowaLsKi, T., 2018. Reservoir evaporation in the Western United States. Bull. Am. Meteorol. Soc. 99, 167–187. https://doi.org/10.1175/BAMS-D-15-00224.1.

Fu, Z., Ciais, P., Prentice, I.C., Gentine, P., Makowski, D., Bastos, A., Luo, X., Green, J.K., Stoy, P.C., Yang, H., Hajima, T., 2022. Atmospheric dryness reduces photosynthesis along a large range of soil water deficits. Nat. Commun. 13, 989. https://doi.org/10.1038/s41467-022-28652-7.

Gimeno, L., Nieto, R., Trigo, R.M., Vicente-Serrano, S.M., López-Moreno, J.I., 2010. Where does the Iberian Peninsula moisture come from? An answer based on a Lagrangian approach. J. Hydrometeorol. 11 https://doi.org/10.1175/2009JHM1182.1.

Grossiord, C., Buckley, T.N., Cernusak, L.A., Novick, K.A., Poulter, B., Siegwolf, R.T.W., Sperry, J.S., McDowell, N.G., 2020. Plant responses to rising vapor pressure deficit. New Phytol. 226, 1550–1566. https://doi.org/10.1111/nph.16485.

Gu, L., Meyers, T., Pallardy, S.G., Hanson, P.J., Yang, B., Heuer, M., Hosman, K.P., Riggs, J.S., Sluss, D., Wullschleger, S.D., 2006. Direct and indirect effects of atmospheric conditions and soil moisture on surface energy partitioning revealed by a prolonged drought at a temperate forest site. J. Geophys. Res. Atmos. 111 https://doi.org/10.1029/2006JD007161.

Guo, X., Meng, D., Chen, X., Li, X., 2022. Validation and comparison of seven land surface evapotranspiration products in the Haihe River Basin, China. Remote Sens. 14 https://doi.org/10.3390/rs14174308.

Gutiérrez, J.M., Jones, R.G., Narisma, G.T., Alves, L.M., Amjad, M., Gorodetskaya, I.V., 2021. Atlas. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

Hamed, K.H.K.H., Ramachandra Rao, A., 1998. A modified Mann-Kendall trend test for autocorrelated data. J. Hydrol. 204, 182–196. https://doi.org/10.1016/S0022-1694(97)00125-X.

Hirschi, M., Seneviratne, S.I., Alexandrov, V., Boberg, F., Boroneant, C., Christensen, O. B., Formayer, H., Orlowsky, B., Stepanek, P., 2011. Observational evidence for soil-moisture impact on hot extremes in southeastern Europe. Nat. Geosci. 4, 17–21. https://doi.org/10.1038/ngeo1032.

Jasechko, S., Sharp, Z.D., Gibson, J.J., Birks, S.J., Yi, Y., Fawcett, P.J., 2013. Terrestrial water fluxes dominated by transpiration. Nature 496, 347–350. https://doi.org/10.1038/nature11983.

Jiménez-Aguirre, M.T., Isidoro, D., 2018. Hydrosaline balance in and nitrogen loads from an irrigation district before and after modernization. Agric. Water Manag. 208, 163–175. https://doi.org/10.1016/j.agwat.2018.06.008.

Kimm, H., Guan, K., Gentine, P., Wu, J., Bernacchi, C.J., Sulman, B.N., Griffis, T.J., Lin, C., 2020. Redefining droughts for the U.S. Corn Belt: the dominant role of atmospheric vapor pressure deficit over soil moisture in regulating stomatal behavior of Maize and soybean. Agric. For. Meteorol. 287, 107930 https://doi.org/10.1016/j.agrformet.2020.107930.

Larsen, E.K., 2021. Transpiration Patterns of *Pinus halepensis* Mill. in Response to Environmental Stresses in a Mediterranean Climate.

Lendzion, J., Leuschner, C., 2008. Growth of European beech (Fagus sylvatica L.) saplings is limited by elevated atmospheric vapour pressure deficits. For. Ecol. Manag. 256, 648–655. https://doi.org/10.1016/j.foreco.2008.05.008.

Lian, X., Piao, S., Li, L.Z.X., Li, Y., Huntingford, C., Ciais, P., Cescatti, A., Janssens, I.A., Peñuelas, J., Buermann, W., Chen, A., Li, X., Myneni, R.B., Wang, X., Wang, Y., Yang, Y., Zeng, Z., Zhang, Y., McVicar, T.R., 2020. Summer soil drying exacerbated by earlier spring greening of northern vegetation. Sci. Adv. 6 https://doi.org/10.1126/sciadv.aax0255 eaax0255.

Liu, L., Gudmundsson, L., Hauser, M., Qin, D., Li, S., Seneviratne, S.I., 2020a. Soil moisture dominates dryness stress on ecosystem production globally. Nat. Commun. 11, 4892. https://doi.org/10.1038/s41467-020-18631-1.

Liu, Y., Kumar, M., Katul, G.G., Feng, X., Konings, A.G., 2020b. Plant hydraulics accentuates the effect of atmospheric moisture stress on transpiration. Nat. Clim. Chang. 10, 691–695. https://doi.org/10.1038/s41558-020-0781-5.

Liu, H., Xin, X., Su, Z., Zeng, Y., Lian, T., Li, L., Yu, S., Zhang, H., 2023. Intercomparison and evaluation of ten global ET products at site and basin scales. J. Hydrol. 617 https://doi.org/10.1016/j.jhydrol.2022.128887.

Lobell, D.B., Schlenker, W., Costa-Roberts, J., 2011. Climate trends and global crop production since 1980. Science (80), 333.

Lorenzo-Lacruz, J., Vicente-Serrano, S.M., López-Moreno, J.I., Morán-Tejeda, E., Zabalza, J., 2012. Recent trends in Iberian streamflows (1945-2005). J. Hydrol. 414–415 https://doi.org/10.1016/j.jhydrol.2011.11.023.

Lu, E., Takle, E.S., 2010. Concurrent variations of water vapor and temperature corresponding to the interannual variation of precipitation in the north American Regional Reanalysis. J. Geophys. Res. Atmos. 115 https://doi.org/10.1029/2009JD012956.

Martens, B., Miralles, D.G., Lievens, H., van der Schalie, R., de Jeu, R.A.M., Fernández-Prieto, D., Beck, H.E., Dorigo, W.A., Verhoest, N.E.C., 2017. GLEAM~v3: satellite-based land evaporation and \hack{\newline}root-zone soil moisture. Geosci. Model Dev. 10, 1903–1925. https://doi.org/10.5194/gmd-10-1903-2017.

Martens, B., Waegeman, W., Dorigo, W.A., Verhoest, N.E.C., Miralles, D.G., 2018. Terrestrial evaporation response to modes of climate variability. NPJ Clim. Atmos. Sci. 1, 43. https://doi.org/10.1038/s41612-018-0053-5.

Martínez-Fernández, J., Ceballos, A., 2003. Temporal stability of soil moisture in a large-field experiment in Spain. Soil Sci. Soc. Am. J. 67, 1647–1656.

Martin-Vide, J., Olcina-Cantos, J., 2001. Climas y tiempos de España. Alianza Editor, 43.

Massmann, A., Gentine, P., Lin, C., 2019. When does vapor pressure deficit drive or reduce evapotranspiration? J. Adv. Model. Earth Syst. 11, 3305–3320. https://doi.org/10.1029/2019MS001790.

Materia, S., Ardilouze, C., Prodhomme, C., Donat, M.G., Benassi, M., Doblas-Reyes, F.J., Peano, D., Caron, L.-P., Ruggieri, P., Gualdi, S., 2022. Summer temperature response to extreme soil water conditions in the Mediterranean transitional climate regime. Clim. Dyn. 58, 1943–1963. https://doi.org/10.1007/s00382-021-05815-8.

McKinnon, K.A., Poppick, A., Simpson, I.R., 2021. Hot extremes have become drier in the United States Southwest. Nat. Clim. Chang. 11, 598–604. https://doi.org/10.1038/s41558-021-01076-9.

Medlyn, B.E., Barton, C.V.M., Broadmeadow, M.S.J., Ceulemans, R., De Angelis, P., Forstreuter, M., Freeman, M., Jackson, S.B., Kellomäki, S., Laitat, E., Rey, A., Roberntz, P., Sigurdsson, B.D., Strassemeyer, J., Wang, K., Curtis, P.S., Jarvis, P.G., 2001. Stomatal conductance of forest species after long-term exposure to elevated CO2 concentration: a synthesis. New Phytol. 149, 247–264. https://doi.org/10.1046/j.1469-8137.2001.00028.x.

Miralles, D.G., Holmes, T.R.H., De Jeu, R.A.M., Gash, J.H., Meesters, A.G.C.A., Dolman, A.J., 2011. Global land-surface evaporation estimated from satellite-based observations. Hydrol. Earth Syst. Sci. 15, 453–469. https://doi.org/10.5194/hess-15-453-2011.

Miralles, D.G., Teuling, A.J., Van Heerwaarden, C.C., De Arellano, J.V.-G., 2014. Mega-heatwave temperatures due to combined soil desiccation and atmospheric heat accumulation. Nat. Geosci. 7, 345–349. https://doi.org/10.1038/ngeo2141.

Novick, K.A., Ficklin, D.L., Stoy, P.C., Williams, C.A., Bohrer, G., Oishi, A.C., Papuga, S. A., Blanken, P.D., Noormets, A., Sulman, B.N., Scott, R.L., Wang, L., Phillips, R.P., 2016. The increasing importance of atmospheric demand for ecosystem water and carbon fluxes. Nat. Clim. Chang. 6, 1023–1027. https://doi.org/10.1038/nclimate3114.

Olcina, J., 1994. Riesgos climáticos en la Península Ibérica. Phentalon, Madrid.

Padrón, R.S., Gudmundsson, L., Decharme, B., Ducharne, A., Lawrence, D.M., Mao, J., Peano, D., Krinner, G., Kim, H., Seneviratne, S.I., 2020. Observed changes in dry-season water availability attributed to human-induced climate change. Nat. Geosci. 13, 477–481. https://doi.org/10.1038/s41561-020-0594-1.

Paredes, D., Trigo, R.M., Garcia-Herrera, R., Trigo, I.F., 2006. Understanding precipitation changes in Iberia in early spring: Weather typing and storm-tracking approaches. J. Hydrometeorol. 7, 101–113. https://doi.org/10.1175/JHM472.1.

Phillips, D.L., Dolph, J., Marks, D., 1992. A comparison of geostatistical procedures for spatial analysis of precipitation in mountainous terrain. Agric. For. Meteorol. 58, 119–141. https://doi.org/10.1016/0168-1923(92)90114-J.

Pinilla, V., 2006. The development of irrigated agriculture in twentieth-century Spain: A case study of the Ebro basin. Agric. Hist. Rev. 54, 122–141.

Ribeiro, A.F.S., Russo, A., Gouveia, C.M., Pires, C.A.L., 2020. Drought-related hot summers: A joint probability analysis in the Iberian Peninsula. Weather Clim. Extrem. 30 https://doi.org/10.1016/j.wace.2020.100279.

Rodriguez-Puebla, C., Encinas, A.H., Nieto, S., Garmendia, J., 1998. Spatial and temporal patterns of annual precipitation variability over the Iberian Peninsula. Int. J. Climatol. 18, 299–316. https://doi.org/10.1002/(SICI)1097-0088(19980315)18:3<299::AID-JOC247>3.0.CO;2-L.

Russo, A., Gouveia, C.M., Dutra, E., Soares, P.M.M., Trigo, R.M., 2019. The synergy between drought and extremely hot summers in the Mediterranean. Environ. Res. Lett. 14 https://doi.org/10.1088/1748-9326/aaf09e.

Sánchez-Salguero, R., Camarero, J.J., Carrer, M., Gutiérrez, E., Alla, A.Q., Andreu-Hayles, L., Hevia, A., Koutavas, A., Martínez-Sancho, E., Nola, P., Papadopoulos, A., Pasho, E., Toromani, E., Carreira, J.A., Linares, J.C., 2017. Climate extremes and predicted warming threaten Mediterranean Holocene firs forests refugia. Proc. Natl. Acad. Sci. U. S. A. 114 https://doi.org/10.1073/pnas.1708109114. E10142–E10150.

Scaini, A., Sánchez, N., Vicente-Serrano, S.M., Martínez-Fernández, J., 2015. SMOS-derived soil moisture anomalies and drought indices: A comparative analysis using in situ measurements. Hydrol. Process. 29 https://doi.org/10.1002/hyp.10150.

Seneviratne, S.I., Lüthi, D., Litschi, M., Schär, C., 2006. Land–atmosphere coupling and climate change in Europe. Nature 443, 205–209. https://doi.org/10.1038/nature05095.

Seneviratne, S.I., Corti, T., Davin, E.L., Hirschi, M., Jaeger, E.B., Lehner, I., Orlowsky, B., Teuling, A.J., 2010. Investigating soil moisture-climate interactions in a changing climate: A review. Earth Sci. Rev. 99, 125–161. https://doi.org/10.1016/j.earscirev.2010.02.004.

Sherwood, S., Fu, Q., 2014. A drier future? Science 343 (80), 737–739. https://doi.org/10.1126/science.1247620.

Sillero-Medina, J.A., Rodrigo-Comino, J., Ruiz-Sinoga, J.D., 2021. Factors determining the soil available water during the last two decades (1997–2019) in southern Spain. Arab. J. Geosci. 14, 1971. https://doi.org/10.1007/s12517-021-08265-y.

Song, X., Lyu, S., Wen, X., 2020. Limitation of soil moisture on the response of transpiration to vapor pressure deficit in a subtropical coniferous plantation subjected to seasonal drought. J. Hydrol. 591, 125301 https://doi.org/10.1016/j.jhydrol.2020.125301.

Sousa, P.M., Barriopedro, D., Ramos, A.M., García-Herrera, R., Espírito-Santo, F., Trigo, R.M., 2019. Saharan air intrusions as a relevant mechanism for Iberian heatwaves: the record breaking events of August 2018 and June 2019. Weather Clim. Extrem. 26, 100224 https://doi.org/10.1016/j.wace.2019.100224.

Stegehuis, A.I., Vautard, R., Ciais, P., Teuling, A.J., Jung, M., Yiou, P., 2013. Summer temperatures in Europe and land heat fluxes in observation-based data and regional climate model simulations. Clim. Dyn. 41, 455–477. https://doi.org/10.1007/s00382-012-1559-x.

Stegehuis, A.I., Vogel, M.M., Vautard, R., Ciais, P., Teuling, A.J., Seneviratne, S.I., 2021. Early summer soil moisture contribution to Western European Summer Warming. J. Geophys. Res. Atmos. 126 https://doi.org/10.1029/2021JD034646 e2021JD034646.

Stocker, B.D., Zscheischler, J., Keenan, T.F., Prentice, I.C., Peñuelas, J., Seneviratne, S.I., 2018. Quantifying soil moisture impacts on light use efficiency across biomes. New Phytol. 218, 1430–1449. https://doi.org/10.1111/nph.15123.

Sulman, B.N., Roman, D.T., Yi, K., Wang, L., Phillips, R.P., Novick, K.A., 2016. High atmospheric demand for water can limit forest carbon uptake and transpiration as severely as dry soil. Geophys. Res. Lett. 43, 9686–9695. https://doi.org/10.1002/2016GL069416.

Teuling, A.J., Seneviratne, S.I., Williams, C., Troch, P.A., 2006. Observed timescales of evapotranspiration response to soil moisture. Geophys. Res. Lett. 33 https://doi.org/10.1029/2006GL028178.

Tomas Burguera, M., Jiménez Castañeda, A., Luna Rico, Y., Morata Gasca, A., Vicente-Serrano, S.M., González Hidalgo, J.C., Begueria, S., Tomás-Burguera, M., Castañeda, A.J., Luna, M.Y., Morata, A., Vicente-Serrano, S.M., Gonzalez-Hidalgo, J. C., Begueria, S., 2016. Control de calidad de siete variables del banco nacional de datos de AEMET. In: Cantos, Olcina, Jorge, Amorós, Rico, Antonio, M., Moltó Mantero, E. (Eds.), Clima, Sociedad, Riesgos y Ordenación Del Territorio. Instituto Interuniversitario de Geografía, Universidad de Alicante; [Sevilla]: Asociación Española de Climatología, Alicante, Spain, pp. 407–415.

Tomas-Burguera, M., Beguería, S., Vicente-Serrano, S.M., 2020. Climatology and trends of reference evapotranspiration in Spain. Int. J. Climatol. https://doi.org/10.1002/joc.6817 n/a.

Trenberth, K.E., Shea, D.J., 2005. Relationships between precipitation and surface temperature. Geophys. Res. Lett. 32, 1–4. https://doi.org/10.1029/2005GL022760.

Vargas Zeppetello, L.R., Battisti, D.S., Baker, M.B., 2019. The origin of soil moisture evaporation "Regimes". J. Clim. 32, 6939–6960. https://doi.org/10.1175/JCLI-D-19-0209.1.

Vicente-Serrano, S.M., Tomas-Burguera, M., Beguería, S., Reig, F., Latorre, B., Peña-Gallardo, M., Luna, M.Y., Morata, A., González-Hidalgo, J.C., 2017. A high resolution dataset of drought indices for Spain. Data 2.

Vicente-Serrano, S.M., Nieto, R., Gimeno, L., Azorin-Molina, C., Drumond, A., El Kenawy, A., Dominguez-Castro, F., Tomas-Burguera, M., Peña-Gallardo, M., 2018.

Recent changes of relative humidity: Regional connections with land and ocean processes. Earth Syst. Dyn. 9, 915–937. https://doi.org/10.5194/esd-9-915-2018.

Vicente-Serrano, S.M., Peña-Gallardo, M., Hannaford, J., Murphy, C., Lorenzo-Lacruz, J., Dominguez-Castro, F., López-Moreno, J.I., Beguería, S., Noguera, I., Harrigan, S., Vidal, J.-P., 2019. Climate, irrigation, and land-cover change explain streamflow trends in countries bordering the Northeast Atlantic. Geophys. Res. Lett. 46, 10821–10833. https://doi.org/10.1029/2019GL084084.

Vicente-Serrano, S., McVicar, T.R., Miralles, D.G., Yang, Y., Tomas-Burguera, M., 2020. Unraveling the influence of atmospheric evaporative demand on drought and its response to climate change. WIREs Clim. Chang. 11, e632 https://doi.org/10.1002/wcc.632.

Villalobos, F.J., Orgaz, F., Testi, L., Fereres, E., 2000. Measurement and modeling of evapotranspiration of olive (Olea europaea L.) orchards. Eur. J. Agron. 13, 155–163. https://doi.org/10.1016/S1161-0301(00)00071-X.

Vogel, M.M., Orth, R., Cheruy, F., Hagemann, S., Lorenz, R., van den Hurk, B.J.J.M., Seneviratne, S.I., 2017. Regional amplification of projected changes in extreme temperatures strongly controlled by soil moisture-temperature feedbacks. Geophys. Res. Lett. 44, 1511–1519. https://doi.org/10.1002/2016GL071235.

Wang, K., Dickinson, R.E., Liang, S., 2012. Global atmospheric evaporative demand over land from 1973 to 2008. J. Clim. 25, 8353–8361. https://doi.org/10.1175/JCLI-D-11-00492.1.

Wang, W., Lee, X., Xiao, W., Liu, S., Schultz, N., Wang, Y., Zhang, M., Zhao, L., 2018. Global lake evaporation accelerated by changes in surface energy allocation in a warmer climate. Nat. Geosci. https://doi.org/10.1038/s41561-018-0114-8.

Weedon, G.P., Gomes, S., Viterbo, P., Shuttleworth, W.J., Blyth, E., Österle, H., Adam, J. C., Bellouin, N., Boucher, O., Best, M., 2011. Creation of the WATCH forcing data and its use to assess global and regional reference crop evaporation over land during the twentieth century. J. Hydrometeorol. 12, 823–848. https://doi.org/10.1175/2011JHM1369.1.

Willmott, C.J., Robeson, S.M., Matsuura, K., 2012. A refined index of model performance. Int. J. Climatol. 32, 2088–2094. https://doi.org/10.1002/joc.2419.

Yang, S., Zeng, J., Fan, W., Cui, Y., 2022. Evaluating root-zone soil moisture products from GLEAM, GLDAS, and ERA5 based on in situ observations and triple collocation method over the Tibetan Plateau. J. Hydrometeorol. 23, 1861–1878. https://doi.org/10.1175/JHM-D-22-0016.1.

Yuan, W., Zheng, Y., Piao, S., Ciais, P., Lombardozzi, D., Wang, Y., Ryu, Y., Chen, G., Dong, W., Hu, Z., Jain, A.K., Jiang, C., Kato, E., Li, S., Lienert, S., Liu, S., Nabel, J.E. M.S., Qin, Z., Quine, T., Sitch, S., Smith, W.K., Wang, F., Wu, C., Xiao, Z., Yang, S., 2019. Increased atmospheric vapor pressure deficit reduces global vegetation growth. Sci. Adv. 5, eaax1396.

Yuan, S., Quiring, S.M., Zhao, C., 2020. Evaluating the utility of drought indices as soil moisture proxies for drought monitoring and land–atmosphere interactions. J. Hydrometeorol. 21, 2157–2175. https://doi.org/10.1175/JHM-D-20-0022.1.

Yue, S., Wang, C.Y., 2004. The Mann-Kendall test modified by effective sample size to detect trend in serially correlated hydrological series. Water Resour. Manag. 18, 201–218. https://doi.org/10.1023/B:WARM.0000043140.61082.60.

Zhao, W., Khalil, M.A.K., 1993. The relationship between precipitation and temperature over the contiguous United States. J. Clim. 6, 1232–1236. https://doi.org/10.1175/1520-0442(1993)006<1232:TRBPAT>2.0.CO;2.

Zhou, S., Williams, A.P., Berg, A.M., Cook, B.I., Zhang, Y., Hagemann, S., Lorenz, R., Seneviratne, S.I., Gentine, P., 2019. Land{\textendash}atmosphere feedbacks exacerbate concurrent soil drought and atmospheric aridity. Proc. Natl. Acad. Sci. 116, 18848–18853. https://doi.org/10.1073/pnas.1904955116.